Sixth Oregon Climate Assessment

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OCCRI

Published January 2023 at Oregon State University, Corvallis, Oregon.

Recommended citation: Fleishman, E., editor. 2023. Sixth Oregon Climate Assessment. Oregon Climate Change Research Institute, Oregon State University, Corvallis, Oregon. https://blogs.oregonstate.edu/occri/oregon-climate-assessments.

Acknowledgments

This sixth Oregon Climate Assessment is consistent with the charge of the Oregon Climate Change Research Institute under Enrolled House Bill 3543 of the 74th Oregon Legislative Assembly.

We are grateful to the many authors, other contributors, reviewers, and advisors to this assessment. We welcome readers to contact us with ideas for ensuring that the sustained assessment process is relevant to their priorities.

Thanks to Dominique Bachelet, Zach Baker, Dan Bigelow, Randall Bluffstone, Annie Hommel, Chas Jones, Jeff Kline, Amelia Marchand, Larry O'Neill, John Punches, David Rupp, Amy Schlusser, and Deepti Singh for reviews of content in this assessment.

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Executive Summary

Established and emerging understanding of observed and projected climate change in Oregon, and knowledge of the opportunities and risks that climate change poses to natural and human systems, may serve as a resource for actions such as equitable planning for mitigation of climate-related natural hazards and implementation of Oregon's 2021 Climate Change Adaptation Framework.

State of Climate Science

Temperature and precipitation. Oregon's annual average temperature increased by about 2.2°F per century since 1895. If greenhouse gas emissions continue at current levels, annual temperature in Oregon is projected to increase by 5°F by the 2050s and 8.2°F by the 2080s, with the greatest seasonal increases in summer. Precipitation is projected to increase during winter and decrease during summer, and the number and intensity of heavy winter precipitation events is projected to increase. Furthermore, the proportion of precipitation falling as rain rather than snow is expected to increase.

Arctic amplification. The contribution to severe weather in Oregon from disproportionately rapid warming in the Arctic (Arctic amplification) is uncertain, but is likely to be small. Some evidence suggests that midlatitude westerly winds are becoming wavier, allowing Arctic air to move south, and that loss of sea ice contributes to extreme winter precipitation. There is greater certainty that Arctic amplification is contributing to summer heat waves and hot, dry autumn weather.

Wind speeds. Wind patterns affect provision of electricity, transportation safety, and the spread of wildfires and pollutants. Mean wind speeds in Oregon are projected to decrease slightly, but extreme winter wind speeds may increase, especially in western Oregon. The frequency of strong easterly winds during summer and autumn, however, is projected to decrease slightly.

Current climate models. Most projections and analysis of future climate impacts still are based on the suite of global climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5), and inferences based on these models remain valid and useful. Projections from models in the sixth phase (CMIP6), which reflect slightly different assumptions about emissions and improved understanding of the Earth system, are being evaluated and are becoming more accessible. As the CMIP6 models are refined, it may become worthwhile to update climate impacts assessments.

Climate-Related Natural Hazards

Extreme temperatures. The number of days that are warmer than 90°F and nights that are warmer than 65°F is increasing across Oregon, although extreme cold will still be possible in the coming decades. The Oregon Occupational Safety and Health Administration's new regulations on workplace heat exposure are based on thresholds of the heat index, which accounts for both air temperature and relative humidity. Warming over extensive areas, rather than increases in relative humidity, is the main driver of projected future increases in extreme heat index values in Oregon.

Drought. Over the past 20 years, the incidence, extent, and severity of drought in the Northwest increased. Low precipitation contributed to each drought, but temperature and snowpack also affected drought severity and impacts on agriculture, fisheries, and other sectors. As summers in Oregon continue to become warmer and drier and mountain snowpack decreases, the frequency of droughts, particularly snow droughts, is likely to increase.

Changes in the water cycle. Since the mid-late 1900s, 20 of Oregon's glaciers disappeared; none remain in the Wallowa Mountains. Glacier retreat accelerated during the past 30 years, in part due to human-caused climate change. Public participation in science, or community science, is a powerful means of filling data gaps and improving models of precipitation and water availability. The Community Collaborative Rain, Hail and Snow network (CoCoRaHS), Community Snow Observations (CSO), and Mountain Rain or Snow are compelling illustrations of public contributions to advancing climate science and its applications.

Wildfire. Total annual area burned in Oregon has increased during the last 35 years. As aridity increases,

the likelihood of extreme fire weather is increasing, and the area burned by lightning-caused fires in central Oregon is projected to increase. Following extensive wildfires in 2020, Oregonians took personal action and also assisted their communities in becoming more resilient. Survey results suggest relative high levels of support for climate mitigation and adaptation policies. Survey results also indicate widespread concerns about the impacts of smoke on personal health and highlight potential benefits of providing public smoke-related information and distributing protective equipment.

Coastal hazards. Relative sea-level rise rates are slower in Oregon than in many other coastal regions of the United States. Nevertheless, sea-level rise threatens buildings and offshore and coastal transportation networks. Additionally, local erosion and flooding along the Oregon coast tends to be high during major winter storm seasons. Adaptation measures being implemented or considered in coastal Oregon include hard structures, natural structures, and nonstructural policies and regulations, such as zoning restrictions and relocation of communities.

Adaptation Sectors

Economics. Understanding the magnitude of the economic effects of climate change is critical for evaluating trade-offs of mitigation and adaptation policies. Climate change may significantly affect the availability and use of water and irrigation in Oregon's agricultural sector and change the composition of Oregon's timberlands. Financial incentives could encourage forest landowners to sequester carbon in a cost-effective manner. Oregon's oceans and coasts can harness wave and offshore wind energy while generating sustained economic profit and job opportunities.

Natural systems. Responses of species and ecosystems to climate change and its interactions with other environmental changes are highly variable. Extreme heat can reduce tree growth and increase tree mortality, but trees' susceptibility is affected by topography, acclimation, water availability, and other factors. The near-term and long-term causes and consequences of foliage scorch and heat stress remain uncertain. Conservation priorities for cold-water fishes, such as salmon and native trout, have tended to discount low elevation, seasonally warm waters. However, water bodies that are too warm for salmonids during summer may be ideal during other seasons. Use of both seasonally cold and warm waters may support growth and persistence of Oregon's native fishes.

Built environment. Because land-use laws control development, they affect mitigation of and resilience to climate change. Recent reforms of Oregon's land-use and housing laws, and related regulations and policy, support reduction of greenhouse gas emissions, carbon sequestration, increasing community resilience, and more equitably distributing environmental benefits and burdens. Full integration of climate science and equity considerations into land-use plans and actions could enable Oregon to respond to climate change even more effectively.

Public health. The composition of wildfire smoke, and therefore its effects on public health, is highly variable. Exposure to wildfire smoke can lead to mortality and adverse respiratory and cardiovascular outcomes, and may affect pregnancy and birth outcomes. Increasing co-occurrence of wildfire smoke and surface ozone during summer can exacerbate negative health outcomes. Such exposures and associated hospital admissions also stress the capacity of the health care system.

Tribal resilience. Climate change places disproportionately high stresses on tribal communities, yet tribal adaptation to environmental and social change over millennia can enable unusually high resilience. Early career tribal citizens and their communities are responding to climate change via ceremony, political action, workforce development, environmental stewardship, and youth education and fellowship, thereby exercising self-determination and reclaiming sovereignty despite inequities.

Social systems. Visual artists are informing viewers about climate change, engaging audiences in conversation and information sharing, and catalyzing cultural evolution and transformation. In Oregon's agricultural sector, efforts to restore and sustainably manage degraded soils (practices often referenced as regenerative agriculture) are expanding. Under some circumstances, these practices also can increase short-term or long-term carbon sequestration.

The full Sixth Oregon Climate Assessment is available at blogs.oregonstate.edu/occri/oregon-climate-assessments.

Introduction

Consistent with its charge under Oregon House Bill 3543, the Oregon Climate Change Research Institute (OCCRI) conducts a biennial assessment of the state of climate change science, including biological, physical, and social science, as it relates to Oregon and the likely effects of climate change on Oregon. This sixth Oregon Climate Assessment builds on the previous assessments by continuing to evaluate past and projected future changes in Oregon's climate and water supply. Like the fifth assessment, it is structured with the goal of supporting the state's mitigation planning for natural hazards and implementation of the 2021 Oregon Climate Change Adaptation Framework.

The first section of this assessment, *State of Climate Science*, reflects OCCRI's sustained appraisal of observed trends and future projections of temperature, precipitation, and other major climate variables. Previous key messages about projected changes in Oregon's climate, such as warmer temperatures, drier summers, and an increase in the frequency, duration, and severity of drought, remain consistent. *State of Climate Science* summarizes emerging evidence related to potential effects of Arctic warming on the state's climate and explores the likelihood of changes in annual and seasonal wind speeds. The section also compares the latest two generations of global climate models, including their assumptions about emissions of greenhouse gases and their accessibility.

The second section of this Oregon Climate Assessment delves into the expected effects of climate change on natural hazards, including extreme temperatures, drought, changes in the water cycle, wildfire, and coastal flooding and erosion. Glaciers and perennial snowfields in Oregon retreated rapidly during the past 30 years, reducing storage of water that otherwise would be released during late summer. The section details the contributions of tens of thousands of weather stations to PRISM, the most widely used source of mapped climate data in the United States, and explains how public participation in science is becoming a powerful means of filling data gaps and improving models of precipitation and water availability. The increasing incidence and size of wildfires, whether ignited by human activity or lightning, are strongly linked to episodic drought and long-term increases in aridity. Two surveys conducted after extensive wildfires in 2020 suggest relatively high support among Oregonians for climate mitigation and adaptation policies. Survey results also indicate widespread concerns about the impacts of smoke on personal health and desires for greater access to smoke-related information and protective equipment.

The third section of this assessment addresses six sectors within which Oregon's 2021 Climate Change Adaptation Framework aggregates vulnerabilities and strategic responses: economy, natural world, built environment and infrastructure, public health, cultural heritage, and social systems. The section begins with a robust discussion of economic concepts and tools relevant to understanding climate challenges and opportunities, and highlights recent insights on the effects of climate change on economic activity in Oregon. Contributions related to natural systems underscore that observations of short-term ecological stress from climate extremes, such as foliage scorch, may or may not indicate long-term effects on mortality and nutrient and water cycles. Furthermore, new research questions whether salmonids in the Pacific Northwest may be more tolerant of high water temperatures than previously assumed. Next, the section investigates how reforms of Oregon's land-use and housing laws are supporting reduction of greenhouse gas emissions, increases in community resilience, and more-equitable distribution of environmental benefits and burdens.

Contributions related to public health in this assessment concentrate on the effects of wildfire smoke on human health and the health care system, and the fact that wildfire smoke and high

surface ozone levels increasingly tend to occur on the same days during summer. The health risks of exposure to fine particulate matter ($PM_{2.5}$) are fairly well understood, but many other uncertainties remain, such as the health effects of repeated smoke exposure and relations between health responses and the composition of smoke. Early career tribal citizens share the ways in which their communities are responding to climate change, exercising self-determination and reclaiming sovereignty despite historic and contemporary inequities. The section also explores how visual artists are communicating with the public about climate change, engaging audiences in conversation and encouraging creative problem-solving. Furthermore, the section examines regenerative agriculture, an increasingly popular set of practices that aims to restore and sustainably manage degraded soils.

Both the Climate Change Adaptation Framework and this assessment recognize that the myriad interactions and feedbacks among natural and human systems are complex and can be difficult to differentiate. An iterative assessment process can indicate the extent to which natural hazards may affect adaptation sectors, and inform selection of actions to maximize livelihoods and well-being.

State of Climate Science: Introduction

Observed and Projected Trends in Climate

Oregon is becoming warmer and, despite relatively stable long-term precipitation totals, drier. Most projections and analysis of future climate still are based on the suite of global climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), an initiative of the World Climate Research Programme that aims to increase understanding of past, present, and future natural and human-caused changes in climate. Later in this section, we describe major differences between models included in the fifth and sixth phases of CMIP. These differences notwithstanding, fundamental projections of future climate have not changed appreciably in the two years since publication of the fifth Oregon Climate Assessment (Dalton and Fleishman 2021).

	2050s		2080s	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Annual	3.6 (1.8, 5.4)	5.0 (2.9, 6.9)	4.6 (2.1, 6.7)	8.2 (4.8, 10.7)
Winter	3.3 (1.6, 5.1)	4.5 (2.4, 6.5)	4.2 (1.8, 6.5)	7.4 (4.2, 9.8)
Spring	3.1 (1.4, 5.0)	4.1 (2.0, 5.9)	3.8 (1.7, 6.0)	6.7 (3.8, 9.2)
Summer	4.5 (2.2, 6.8)	6.3 (3.6, 8.9)	5.5 (2.7, 8.3)	10.2 (6.5, 13.9)
Autumn	3.7 (1.5, 5.4)	5.2 (2.6, 7.0)	4.7 (2.0, 6.9)	8.6 (4.6, 11.4)

Table 1. Projected future changes in mean annual and seasonal temperature (°F) in Oregon from the historical baseline (1970–1999) for the 2050s (2040–2069) and 2080s (2070–2099) under RCP 4.5 and RCP 8.5. Values are the average changes from 35 global climate models and the 5th to 95th percentile range across those models. Table reproduced from Dalton et al. 2017, with data for Oregon from Rupp et al. 2017. Winter includes December, January, and February; spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November.

Oregon's average annual temperature increased at a rate of 2.2°F (1.2°C) per century from 1895–2021 (NCEI 2022). Oregon's temperatures are projected to increase in all seasons, particularly summer. If current levels of emissions of greenhouse gases continue throughout the twenty-first century—a scenario referenced by CMIP5 as representative concentration pathway (RCP) 8.5—Oregon's annual average temperature is projected to increase by 5°F (2.8°C) by the 2050s and 8.2°F (4.6°C) by the 2080s (Table 1, Figure 1a). Summer temperatures are projected to increase by 6.3°F (3.7°C) by the 2050s and 10.2°F (5.7°C) by the 2080s under RCP 8.5 (Table 1). A second emissions scenario reflected in these projections, RCP 4.5, represents moderate reductions in global greenhouse gas emissions, with a peak near mid-century.

Oregon's annual precipitation varies considerably among years, and has not changed significantly over the observational record (increase of 0.30 in [0.76 cm] per century from 1895–2021) (NCEI 2022). Some statistically significant increases in heavy precipitation have been documented

	2050s		2080s	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Annual	1.9 (-4.9, 9.0)	2.7 (-6.0, 11.4)	3.4 (-5.6, 15.3)	6.3 (-5.2, 19.9)
Winter	4.9 (-6.4, 16.5)	7.9 (-4.7, 24.3)	7.3 (-6.3, 19.9)	14.5 (-2.8, 37.1)
Spring	1.9 (-8.9,12.1)	2.7 (-7.2, 17.4)	3.4 (-7.7, 14.9)	3.6 (-9.4, 15.6)
Summer	-6.3 (-28.5, 16.1)	-8.7 (-33.1, 22.5)	-4.6 (-24.2, 22.3)	-7.7 (-38.7, 33.5)
Autumn	0.5 (-17.0, 14.4)	-0.8 (-17.1, 14.9)	1.5 (-15.0, 18.1)	1.9 (-17.2, 24.2)

Table 2. Projected future relative changes in total annual and seasonal precipitation (%) in Oregon from the historical baseline (1970–1999) for the 2050s (2040–2069) and 2080s (2070–2099) under RCP 4.5 and RCP 8.5. Values are the average changes from 35 global climate models and the 5th to 95th percentile range across those models. Table reproduced from Dalton et al. 2017, with data for Oregon from Rupp et al. 2017. Winter includes December, January, and February; spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November.

in Oregon (Dalton et al. 2017). However, the relatively small sample sizes and substantial variability in intense precipitation makes it difficult to detect long-term observed trends, and results often depend on location, time frame, and definition of heavy precipitation (Mote et al. 2013). Annual variability is expected to continue to dominate annual precipitation, with a slight increasing trend (Table 2, Figure 1b). Precipitation is expected to increase during the wet season and decrease during summer in the Columbia River basin (Rupp et al. 2017) and, on average, across Oregon as a whole (Table 2). In general, the intensity of heavy precipitation events during the twenty-first century in Oregon is projected to increase, although not uniformly across the state (Dalton et al. 2017, Cooley and Chang 2021).

Recent Advances in Climate Science

Whether disproportionate warming of the Arctic contributes to severe weather at lower latitudes has become a subject of considerable interest and inquiry in recent years. Accordingly, in the next contribution in this section, Rupp and Schmittner examine whether Arctic amplification may affect Oregon's climate.

This section then addresses potential future changes in local wind speeds across Oregon, a topic highly relevant to the risks of wildfires and wildfire smoke. Mean near-surface wind speeds are expected to decrease slightly, but the mean is not necessarily indicative of the maximum speed. Therefore, Rupp investigates drivers, projections, and uncertainties related to wind patterns across the state. Dalton and Bachelet conclude the section by discussing the newest generation of climate models and projections.

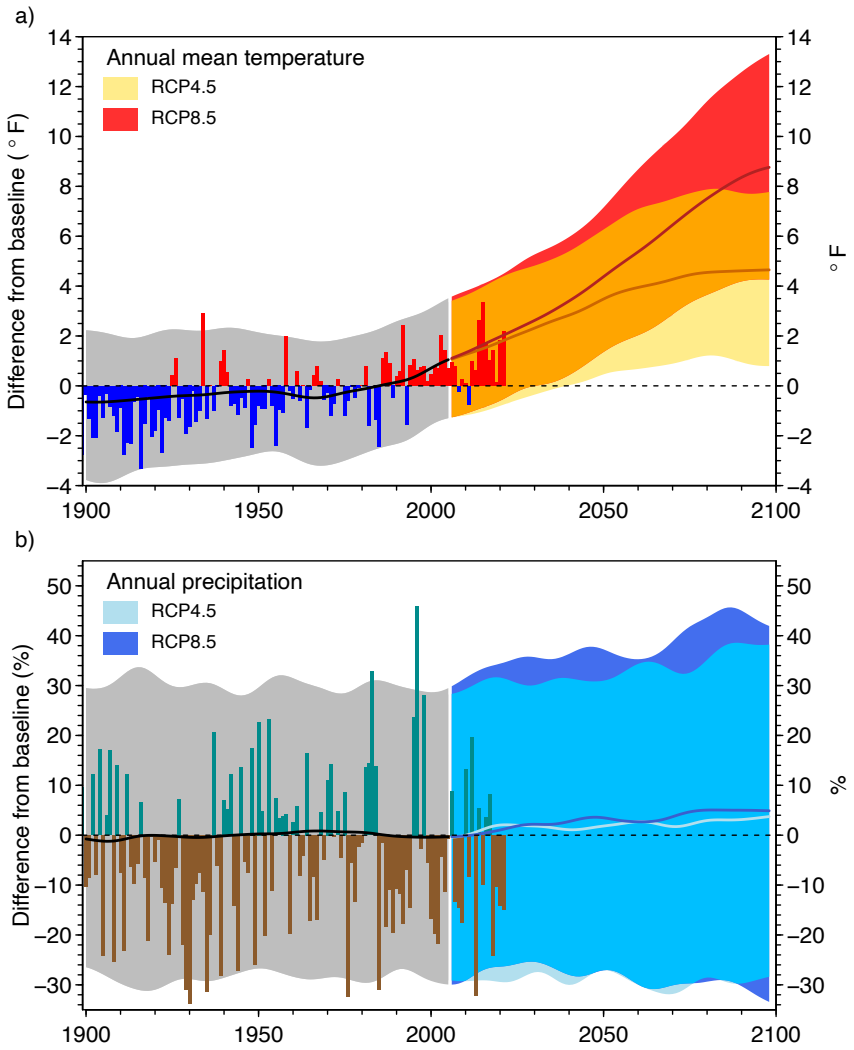

Figure 1. Observed, simulated, and projected changes in Oregon's mean annual (a) temperature and (b) precipitation relative to 1970–1999 (baseline) under RCP 4.5 and RCP 8.5. Colored bars are observed values from the National Centers for Environmental Information. The solid lines are the mean values of simulations from 35 climate models for the years 1900–2005, which were based on observed climate forcings (black line), and 2006–2099. Shading indicates the range in values from all models. The mean and range were smoothed to emphasize long-term variability.

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Arctic Amplification

David E. Rupp and Andreas Schmittner

The Arctic is warming faster than other latitudes. This phenomenon, Arctic amplification, is largely a consequence, and a cause, of disappearing sea ice (Figure 1). As atmospheric concentrations of anthropogenic greenhouse gases and air temperatures increase, existing sea ice melts and formation of new sea ice is inhibited. This process leads to yet more warming because the exposed ocean reflects much less solar energy back to space than sea ice (e.g., Cohen et al. 2020). Another cause of Arctic amplification is the increase in equator-to-pole transport of water vapor that occurs as global temperatures increase. This additional water vapor brings more latent heat northward, and the heat is released when the water vapor condenses in the colder polar air (e.g., Schmittner and Stocker 1999, Siler et al. 2018).

Figure 1. Sea ice off Alaska. Source: U.S. Bureau of Ocean Energy Management.

There is no doubt that Arctic amplification is occurring. But whether it contributes to severe weather at latitudes below the Arctic (below about 66.5°N), particularly in the midlatitudes (roughly 30–60°N), is uncertain. Such a contribution first was hypothesized about a decade ago. Because Arctic amplification decreases the difference in temperature between the equator and pole, a difference that drives the midlatitude westerly winds, it was hypothesized that the intensity of the westerlies will weaken, leading circulation of the air around the planet at the midlatitudes to become slower and wavier or more sinuous. Such planetary waves in the flow of air around the Northern Hemisphere would allow warm air from the south to move northward and cold air from the north to move southward. Therefore, it was hypothesized that the incidence of more-extreme weather, including heat waves and cold snaps, will increase, especially when a large wave persists in place for a long period of time (Francis and Vavrus 2012). However, the decrease in the equator-to-pole temperature gradient may be limited to the lower troposphere, the lowest part of the atmospheric layer that is closest to Earth's surface. In contrast, a robust modeled response to increasing greenhouse gas concentrations is an equator-to-pole temperature gradient that increases in the upper troposphere because the upper troposphere over the tropics warms more quickly than the upper troposphere over the Arctic. Because any effect on planetary waves of the decrease in the temperature gradient in the lower troposphere may be negated by the increase in the temperature gradient in the upper troposphere, the intensity and waviness of the westerlies may not change much (Lee et al. 2021).

A second, more complex hypothesis about the effect of Arctic amplification involves the stratospheric polar vortex, a band of strong westerly winds circling the North Pole in winter at an altitude of 16–48 km (10–30 mi). These strong winds help to retain cold stratospheric air (air in the layer above the troposphere) within the vortex. If changes in sea ice and regional snow weaken or disrupt the stratospheric polar vortex, it is hypothesized that cold, high-altitude polar air then may move southward and downward (Cohen et al. 2020).

These hypotheses, particular the waviness hypothesis, have been mentioned frequently in media reports on the role of climate change in extreme weather events (Blackport and Screen 2020). However, there is disagreement in the scientific community over the effect of Arctic amplification on midlatitude extreme weather (Cohen et al. 2020). Much of the recent contention centers on claims that Arctic amplification has caused extreme cold snaps. For example, a study attributing the cold snap that affected Texas in February 2021 to Arctic amplification (Cohen et al. 2021) was quickly challenged because it inferred a connection that was not supported by the authors' own analysis and because the claim that Arctic amplification will increase frequency of extreme cold events is inconsistent with past studies (Blackport et al. 2022). Moreover, the occurrence of extreme cold events has decreased over most midlatitude terrestrial areas (van Oldenbourgh et al. 2019).

An observed correlation between the downward trend in sea ice cover and an increasingly wavy circulation prompted the waviness hypothesis (Francis and Vavrus 2012). Since the hypothesis was proposed, the large majority of observation-based studies have yielded evidence consistent with a connection between Arctic amplification and extreme winter weather (Cohen et al. 2020). Nevertheless, inferences of studies based on climate modeling have not converged, with slightly fewer indicating that Arctic amplification has a strong influence on extreme winter weather than that it does not (Cohen et al. 2020). Here, we review studies published since 2020, concluding with possible implications for climate and extreme weather in Oregon.

Several recent climate modeling studies reexamined the connection between Arctic amplification and atmospheric circulation during winter in the Northern Hemisphere. For example, Arctic sea-ice loss weakened westerlies from 50–65°N but strengthened those around 30–45°N, although the overall response of atmospheric circulation to Arctic amplification was weak (Smith et al. 2022). Another two studies suggested that in the North Pacific, Arctic amplification leads to strengthening and eastward extension of the North Pacific jet (30–50°N) during winter (Ronalds et al. 2020, Rodriquez Solis et al. 2022). A stronger and more eastward jet is associated with fewer anomalously cold temperatures over the United States and Canada and an increase in the frequency of the North America dipole pattern: relatively warm temperatures in the west and northwest and relatively cool temperatures in the east and southeast (Ronalds et al. 2020).

The results of the above studies were consistent with the hypothesized link between Arctic amplification and a weakening of the westerlies, at least north of ~45°N. However, Blackport and Screen (2020) did not find that reducing the difference between equatorial and polar temperature in a climate model induced more waviness, although mid- to high-latitude westerlies weakened. Furthermore, Blackport and Screen (2020) reported that the observed apparent trend toward wavier circulation has reversed in recent years even as Arctic amplification has continued. Dai and Deng (2021) found that although modeled Arctic amplification decreased the equator-to-pole temperature gradient, it also decreased the variability of the gradient, which in turn decreased the variability in the flow of heat energy. Consequently, variability in winter temperature decreased, with fewer events that were extremely cold or hot relative to the mean temperature. Similarly, Blackport et al. (2021)

discovered that winter temperature variability in the mid to high latitudes has already decreased and that the decrease is attributable to human activity.

Additionally, Arctic amplification may affect midlatitude winter precipitation extremes. Climate models indicated that the effect of sea ice loss on the North Pacific jet brings atmospheric rivers closer to the west coast of North America, although the storm track shifts northeast, increasing precipitation in Canada and the northwestern corner of the United States and decreasing precipitation in the southwestern United States (Ma et al. 2021). On the basis of observations, Liu et al. (2021) concluded that Arctic amplification has increased the amplitude of planetary waves and that Arctic amplification will lead to future increases in extreme precipitation over the Northern Hemisphere, although they did not find a significant effect on precipitation over the northwestern United States.

Although much of the focus has been on winter, climate modeling indicates that Arctic amplification contributed to an increase in the frequency of summer heat waves over North American midlatitudes (Song et al. 2021, Wu and Li 2022). Wang et al. (2022) even attributed the persistent high-pressure ridge that led to the heat wave over British Columbia and the northwestern United States in summer 2021 to ice loss in the Chukchi Sea. The processes that link Arctic amplification to development of a high-pressure ridge over the western United States may also drive the increasing frequency of fire weather during autumn in the lower to midlatitudes of northern Mexico, the United States, and Canada (Zou et al. 2021).

On the whole, the likely effect of Arctic amplification on Oregon's future climate and weather appears to be small. South of ~60°N, the effect of Arctic amplification on the climate is minor. The observed correlation between Arctic amplification and midlatitude extreme weather may not be causal, but reflect that both are affected by greenhouse gas-induced warming and short-term climate variability (Dai and Song 2020). Nevertheless, Arctic amplification, in isolation from other factors driving regional climate change, may decrease the number of winter cold snaps (Dai and Deng 2021, Song et al. 2021) and increase the number of summer heat waves in Oregon (Song et al. 2021, Wang et al. 2022, Wu and Li 2022). Arctic amplification will also promote hot and dry autumn weather that is conducive to wildfires, maybe more so in eastern than in western Oregon (Zou et al. 2021). Arctic amplification's impact on extreme precipitation may be negligible given that Oregon is near the transition zone between increasing atmospheric river frequency to the north and decreasing frequency to south (Ma et al. 2021).

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Projected Changes in Wind Speeds

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Wind patterns in the northwestern United States affect natural disturbances, public health, and multiple sectors. For example, variability in winds affects generation of wind power and, via downed power lines, the reliability of electricity transmission. Changes in winds affect the safety of transportation by air, land, and sea and the spread of wildfires and pollutants, including wildfire smoke and allergens (Figure 1). In Oregon, mean near-surface wind speeds are expected to decrease slightly in the future in response to global climate change (Pryor et al. 2012, Jeong and Sushama 2019, Chen 2020, Mass et al. 2022). However, this decrease in the mean wind speed may not translate to a decrease in strong and extreme winds. Although projections are highly uncertain, climate models tend to agree that the magnitude of extreme wind speed will increase in western Oregon (Pryor et al. 2012, Jeong and Sushama 2019). An extreme wind refers to an annual maximum wind speed with a given probability of being exceeded, such as 5 percent probability of exceedance (a 20-year mean return period) or 2 percent probability of exceedance (a 50-year mean return period). Such increases are not projected in eastern Oregon.

Figure 1. Wind-driven wildfires in Oregon during September 2020 as captured by the Aqua satellite. Source: NASA Worldview.

Oregon's location accounts for some of the uncertainty in the response of strong winds to human-caused emissions of greenhouse gases. In Oregon, the most severe windstorms occur from October through April and are associated with extratropical cyclones (cyclones that occur from 30–60° latitude) (Read 2003, 2007; Mass and Dotson 2010). Although future changes in wind speeds in extratropical cyclones are expected to be small, the projected poleward shift in the storm tracks of these cyclones could lead to substantial changes in extreme wind speeds in some regions (Seneviratne et al. 2021). Whether the speed of strong winds in Oregon changes depends

on the current and future mean and variability of the storm tracks' locations. One study indicated that by 2081–2099 relative to 1981–1999, assuming a high emissions scenario (RCP 8.5), explosive extratropical cyclones—those that generate severe winds—will shift northward by an average of 2.2° over the North Pacific (Seiler and Zwiers 2016). Therefore, explosive extratropical cyclones will become more frequent north of 45°N and less frequent and weaker south of 45°N. Oregon lies between about 42°N and 46°N. Accordingly, although Seiler and Zwiers (2016) did not examine the landfall location of these severe cyclones, the value of 45°N implies high uncertainty in whether the frequency of severe landfalling extratropical cyclones in Oregon will change.

The intensity of strong offshore (easterly) winds typically is less than that of winter wind storms. Nevertheless, offshore winds play a major role in summer heat waves in Oregon, including the record-breaking June 2021 heat wave (Chang et al. 2022), because they displace cooler marine air west of the Cascade Range (Brewer and Mass 2016). Projections from global climate models, assuming RCP 8.5, suggest a decrease in the frequency of strong offshore winds over western Oregon and Washington in July and August, with a ~50 percent reduction from 1970–1999 to 2071–2100 in the number of days with an easterly 850-hPa wind above 5 m sec^{-1} (Brewer and Mass 2016).

In late summer and autumn and prior to the onset of the autumn rains, particularly strong and dry easterly winds, known colloquially as east winds, promote the rapid spread of wildfire. East winds were key drivers of the largest wildfires on record in western Oregon, including the 2020 Labor Days fires (Abatzoglou et al. 2021, Mass et al. 2021, Reilly et al. 2022). Recent research incorporating regional climate models that accounted for the effects of the Cascade Range shed light on the potential human influence on east winds. Model results indicated that from the preindustrial to the current era, the frequency of autumn (September through November) east winds along the Cascade Range in Oregon decreased by ~2 percent (Hawkins et al. 2022). The latter research defined east winds as those with a 700-hPa horizontal speed $u \geq 13$ m sec^{-1}, a 700-hPa vertical speed greater than $\omega \geq 0.6$ Pa sec^{-1} (positive ω in pressure per time coordinates is downward), and near-surface relative humidity ≤ 30%. By the year 2099 relative to 1970, assuming RCP 8.5, the frequency of 10-m easterly winds with a daily maximum exceeding 3.4 m sec^{-1}, which is one standard deviation above the mean, decreased modestly west of the Cascade Range (Mass et al. 2022). For example, in Alpine, Washington, the annual number of days with such winds decreased from 15 to 11 (Mass et al. 2022).

Despite recent advances, understanding of how anthropogenic emissions may affect local winds in Oregon remains limited. Due to their coarse spatial resolution, global climate models and all but the highest-resolution regional climate models cannot adequately simulate mountain slope and valley winds, coastal winds, sea breezes, and winds associated with mesoscale convective systems (Doblas-Reyes et al. 2021). Large numbers of simulations from multiple high-resolution (1 to 10 km [0.6 to 6 mi]) regional climate models ultimately will be required to estimate, with high confidence, changes in these types of winds across Oregon.

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Understanding the Most Current Climate Projections

Meghan Dalton and Dominique Bachelet

Introduction

The Coupled Model Intercomparison Project (CMIP), an initiative of the World Climate Research Programme that aims to increase understanding of past, present, and future natural and human-caused changes in climate, is in its sixth phase (CMIP6). CMIP6 is the climate modeling foundation for the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC; 2021). The fifth phase of CMIP (CMIP5) was the climate modeling foundation for the IPCC's fifth assessment report (2013). Climate modeling institutions worldwide build different global climate models to simulate the future climate given a common set of scenarios of concentrations of greenhouse gases, aerosols, and other external influences on the global climate (climate forcings). Evaluation of climate projections from multiple models in that coordinated set of simulations or experiments improves understanding of the likelihood of various aspects of climate change.

Participating in CMIP6 are 132 models from 49 modeling institutions (pcmdi.llnl.gov/CMIP6/ArchiveStatistics/esgf_data_holdings). By comparison, CMIP5 included 61 models from 28 modeling institutions (pcmdi.llnl.gov/mips/cmip5/availability.html). The global climate science community strives to maintain continuity across phases of CMIP. All global climate models included in CMIP5 and CMIP6 ran historical simulations and standardized DECK (Diagnostic, Evaluation and Characterization of Klima—climate in Ancient Greek) experiments, which evaluated the models' variability, climate sensitivity, and performance (Taylor et al. 2012, Eyring et al. 2016). The institutions participating in CMIP adopted common standards for data, documentation, and software (Eyring et al. 2016).

Here, we describe key differences between CMIP6 and CMIP5 in terms of experimental design, greenhouse gas scenarios, climate models, projections of future climate, and climate sensitivity (the extent to which global temperature is affected by a given change in concentrations of greenhouse gases). We also offer guidance on use of CMIP6 climate projections in climate impacts assessments and describe downscaled CMIP6 data that currently are available.

Experimental Design

CMIP6 has three foci: how the Earth system responds to forcings; systematic model biases; and future climate change considering internal variability, predictability, and uncertainty in scenarios. CMIP6 concentrates on clouds, circulation, and climate sensitivity; melting ice; climate extremes; changes in water availability; regional sea level change; biogeochemistry; and near-term prediction. These science priorities are addressed through 21 model intercomparison projects (MIPs) that isolate a particular facet of the Earth system (for example, aerosol chemistry, cloud feedbacks, or ice sheets) to better understand and quantify its uncertainty and contribution to climate change. Many of the MIPs were continued from CMIP5 (Eyring et al. 2016).

Of the 21 MIPs, ScenarioMIP is the primary MIP that will be used in climate impacts assessments. ScenarioMIP is dedicated to multi-model projections of future climate that are based on alternative scenarios of future emissions and land-use changes. This coordinated project selected a set of scenarios to be used by all participating modeling institutions to produce climate projections that are the foundation for investigation of climate impacts, vulnerability, adaptation, and mitigation by the

research community (O'Neill et al. 2016). Twenty-eight modeling institutions contributed results to ScenarioMIP as part of CMIP6, whereas 19 modeling institutions participated in CMIP5's analogous experiments (Chen et al. 2021). Differences in climate projections between CMIP6 and CMIP5 are due to differences in model structure and type, such as general circulation models or Earth system models (see below), emissions scenarios, and initial conditions and years of the future scenarios (2015 for CMIP6, 2006 for CMIP5) (O'Neill et al. 2016).

Greenhouse Gas Scenarios

The scenarios used in ScenarioMIP are related to those that drove the CMIP5 models, which were based on four representative concentration pathways (RCPs). RCPs are concentrations of greenhouse gases, aerosols, and other factors that determine radiative forcings by 2100. Radiative forcing is the total amount of energy retained in the atmosphere after absorption of incoming solar radiation, which is affected by the reflectivity of Earth's surface, and emission of outgoing long-wave radiation, which is affected by the concentrations of heat-trapping or greenhouse gases. The four RCPs, 2.6, 4.5, 6.0, and 8.5, represent radiative forcings of 2.6, 4.5, 6.0, and 8.5 watts per square meter (W m^{-2}) by 2100, respectively. The most commonly used RCPs, 4.5 and 8.5, are often described as representing moderate reductions and business-as-usual increases in greenhouse gas emissions, respectively. The RCPs do not specify a particular set of social and economic assumptions that would result in the radiative forcing by 2100. Multiple sets of social and economic assumptions could result in the same radiative forcing.

In CMIP6, each of the four radiative forcing levels of the RCPs, plus four additional radiative forcing levels (1.9, 3.4, 3.4 overshoot [OS], and 7.0), was paired with one of five sets of assumptions about future population, technological, and economic growth (Table 1). These assumptions are referenced as Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2016). SSP1 assumes few challenges to mitigation and adaptation. SSP2 assumes continuation of historical social and economic trends, with moderate challenges to mitigation and adaptation, whereas SSP3 assumes conflicts among regions and substantial challenges to mitigation and adaptation. SSP4 assumes inequality within and among countries and minor challenges to mitigation, but substantial challenges to adaptation, and SSP5 assumes dependence on fossil fuels with substantial challenges to mitigation, but minor challenges to adaptation (O'Neill et al. 2016). Each SSP results in a trajectory of greenhouse gas emissions independent of climate policy. The radiative forcing levels represent climate policy outcomes. Some forcing levels are not feasible for a given SSP. For example, only SSP5 can achieve 8.5 W m^{-2} radiative forcing by 2100, and only SSP1 and SSP2 can limit radiative forcing to 1.9 W m^{-2} by 2100.

2100 forcing level (W m^{-2})	SSP1	SSP2	SSP3	SSP4	SSP5
8.5	n/a	n/a	n/a	n/a	SSP5-8.5
7.0	n/a		SSP3-7.0	n/a	
6.0				SSP4-6.0	
4.5		SSP2-4.5			
3.4				SSP4-3.4	SSP5-3.4-OS
2.6	SSP1-2.6		n/a		
1.9	SSP1-1.9		n/a	n/a	n/a

Table 1. The combinations of shared socioeconomic pathways (SSPs) and radiative forcing levels by the year 2100 chosen for CMIP6 projections of future climate. n/a, combination of SSP and radiative forcing level is not feasible. Forcing levels 8.5, 6.0, 4.5, and 2.6 correspond to the four RCPs. Adapted from Chen et al. 2021.

Eight SSP-forcing level combinations were selected for CMIP6 projections of future climate (Table 1). Four scenarios (SSP1-2.6, 2-4.5, 3-7.0, and 5-8.5; the number after the dash corresponds to the forcing level) were the basis for projections of future climate in ScenarioMIP. These four scenarios span a wide range of uncertainty in future forcings and are similar to the RCPs that drove CMIP5. Four additional scenarios (SSP1-1.9, 4-3.4, 5-3.4-OS, and 4-6.0) were considered lower priorities (O'Neill et al. 2016) and will be simulated by institutions contributing to ScenarioMIP only after they complete simulations of the higher-priority scenarios. Of the 56 models participating in ScenarioMIP, 39 have contributed data for the four high-priority scenarios. The four scenarios similar to the RCPs from CMIP5, plus SSP1-1.9, are the core set of scenarios in the IPCC's sixth assessment report (Chen et al. 2021).

The SSPs paired with radiative forcing levels produce trajectories of greenhouse gas emissions that result in different degrees of warming by 2100 (Figure 1). SSP1-1.9 assumes that the Paris Agreement goal of limiting warming to 1.5°C (2.7°F) by 2100 relative to the 1850–1900 mean global temperature is met, with net-zero carbon dioxide emissions by the middle of the twenty-first century. SSP1-2.6 limits warming to 2.0°C (3.6°F) by 2100, with net-zero carbon dioxide emissions by the second half of the century. It is slightly warmer than RCP 2.6. In SSP2-4.5, as in RCP 4.5, carbon dioxide emissions plateau and then gradually decline by mid-century. SSP3-7.0 assumes that carbon dioxide emissions double by 2100, and SSP5-8.5 that carbon dioxide emissions double by 2050. SSP5-8.5 has higher carbon dioxide emissions but lower emissions of other greenhouse gases than RCP 8.5, and is marginally warmer (O'Neill et al. 2016, Chen et al. 2021) (Figure 1).

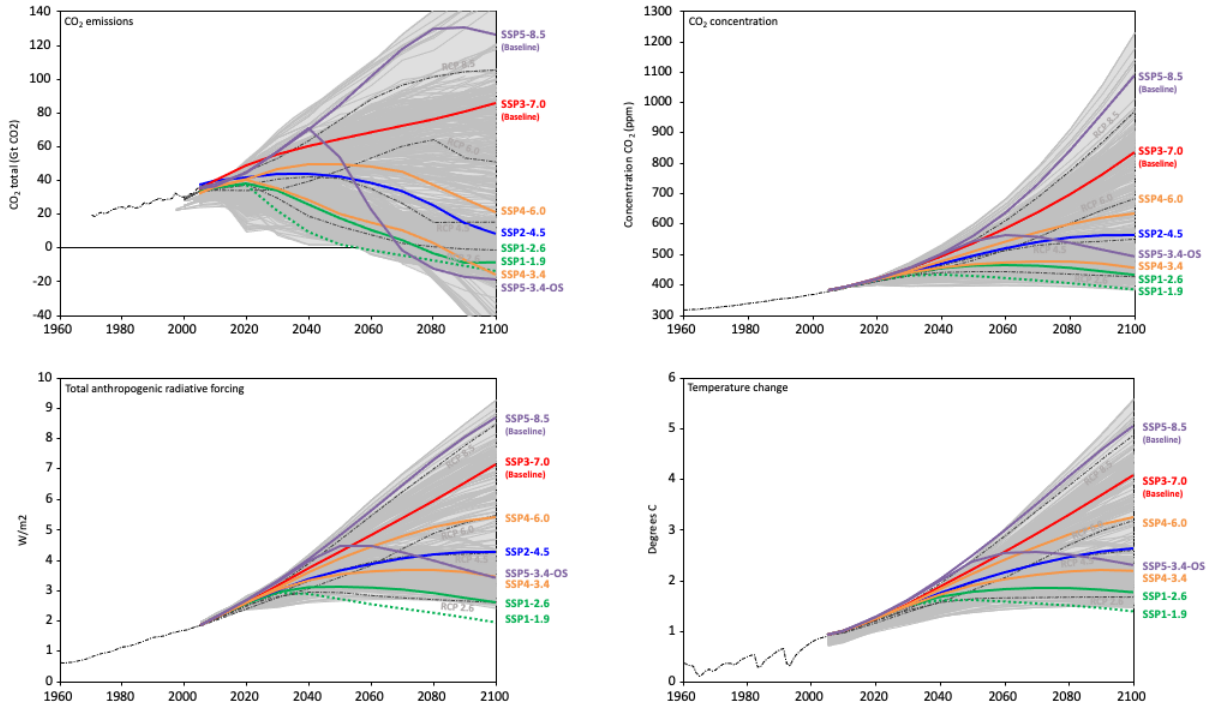

Figure 1. Carbon dioxide emissions (top left) and concentrations (top right), human-caused radiative forcing (bottom left), and global mean temperature (bottom right) for the twenty-first century scenarios in ScenarioMIP (Riahi et al. 2017). Gray areas represent the range of scenarios included in the IPCC's fifth assessment report (Clarke et al. 2014). Source: O'Neill et al. 2016.

Climate Model Advances in CMIP6

Relative to the CMIP5 models, the CMIP6 climate models include many improvements to atmospheric and oceanic circulation and to stratospheric processes (Chen et al. 2021). For example, most CMIP6 models have higher horizontal resolution in the atmosphere, ranging from 50 to 260 km (31–162 mi). Among the exceptions is CanESM5, which maintained the same relatively coarse horizontal resolution as its predecessor (approximately 250 km [155 mi]) to facilitate the production of large ensembles (Swart et al. 2019). CMIP6 models also have a greater number of vertical levels in the atmosphere (14–102), with the top of the atmosphere at 29–88 km (18–55 mi) above Earth's surface (Gutiérrez and Tréguier 2021).

Climate models generally refer to both general circulation models (GCMs) and Earth system models (ESMs). GCMs simulate the dynamics of interactions between the atmosphere and the land and ocean, whereas ESMs also simulate more-detailed chemical and biological processes that interact with the physical climate (Heavens et al. 2013). CMIP6 climate models include improved representation of cloud and aerosol microphysics, ocean eddies, sea ice, and ice sheets (Chen et al. 2021). Not only are there more ESMs in CMIP6 than in CMIP5, but CMIP6 models better represent atmospheric chemistry, carbon and nitrogen cycles, dynamic vegetation and wildfires, and ocean biogeochemistry (Chen et al. 2021, Gutiérrez and Tréguier 2021). Several of the ESMs included in CMIP5 were capable of representing temporal variation in vegetation and simulating vegetation responses to novel climate conditions. However, because the teams that developed these models did not have sufficient time to test the models, vegetation was treated as static rather than dynamic. Similarly, most of the ESMs included in CMIP5 did not include a wildfire submodel. The majority of those included in CMIP6, by contrast, simulated wildfires, allowing land cover to change abruptly and affect land surface reflectivity, point-source emissions, and, in turn, atmospheric chemistry. It is ideal to represent the nitrogen cycle in ESMs to account for the response of vegetation to increasing levels of atmospheric carbon dioxide, which reduces the extent to which nutrient limitation constrains plant growth. Most of the ESMs in CMIP6, in contrast with those in CMIP5, include the nitrogen cycle. However, the level of sophistication in their treatment of the cycle varies greatly, and agreement between models needs to be improved (Davies-Barnardet al. 2022).

Simulation of observed mean temperature trends and variability in global climate models has become more accurate (IPCC 2021). CMIP6 models also simulate past temperature and precipitation extremes more accurately than CMIP5 models (Chen et al. 2020, Fan et al. 2020). The area of the Northern Hemisphere covered by snow generally was simulated fairly well in CMIP5, but CMIP6 models performed better (Mudryk et al. 2020, Zhu et al. 2021). Simulation of Northern Hemisphere storm tracks improved in CMIP6, although the spatial patterns of future storms are similar to those in CMIP5 (Harvey et al. 2020). Moreover, CMIP6 models can reasonably simulate a range of observed atmospheric circulation patterns over the Pacific Northwest, and the temperature and precipitation anomalies associated with those circulation patterns (Taylor et al. 2022).

Climate Sensitivity

One measure of climate sensitivity, the equilibrium climate sensitivity (ECS), is an estimate of the temperature response to carbon dioxide concentrations that have doubled, and remained so, after stabilization of temperature over hundreds or thousands of years. On the basis of observations, paleoclimate data, and other evidence, the ECS of Earth was assessed to be within 2.5–4.0°C (4.5–7.2°F) (66 percent likelihood) or 2.0–5.0°C (3.6–9.0°F) (90 percent likelihood) (Forster et al. 2021).

The scientific community typically evaluates climate model outputs on the basis of how close they are to this assessed range of ECS. Some climate models are more sensitive than others: they produce greater warming given the same concentration of greenhouse gases.

The range of ECS is 1.8–5.6°C (3.2–10.0°F) among CMIP6 models and 2.1–4.7°C (3.8–8.5°F) among CMIP5 models (Meehl et al. 2020, Zelinka et al. 2020). The average ECS value of the CMIP6 model ensemble is higher than both the assessed average value and the CMIP5 model results (Forster et al. 2021). ECS values in all CMIP5 models were less than 5°C (9°F), whereas about one-fifth of the CMIP6 models had an ECS above 5°C (9°F) (Hausfather et al. 2022). Cloud feedbacks and cloud-aerosol interactions most likely are the primary contributors to the higher sensitivities (Meehl et al. 2020, Zelinka et al. 2020). Although there is a 5 percent likelihood that Earth's ECS could be above 5°C, the CMIP6 climate models with ECS >5°C overestimate the observed warming and are considered less valid and reliable than those with ECS ≤5°C. Consequently, use of the average and range of the CMIP6 model ensemble would not be appropriate for analyzing projections of future climate (Hausfather et al. 2022). Before averaging temperature projections from the CMIP6 models, the IPCC weighted the projections on the basis of how well each model simulated historical observations. This approach prevented CMIP6 models with ECS >5°C from skewing the ensemble average (Hausfather et al. 2022). When using ouputs of individual CMIP6 climate models or interpreting published results that were based on CMIP6 climate models, the models' climate sensitivity and their skill in simulating past climate is central to evaluation of reliability (Tokarska et al. 2020, Hausfather et al. 2022).

Projections of Future Climate and Effects of Climate Change

Comparisons of future climate as projected by CMIP6 and CMIP5 are facilitated by ScenarioMIP's inclusion of three scenarios designed to provide continuity between the CMIPs: SSP1-2.6, SSP2-4.5, and SSP5-8.5. These comparisons are useful despite different initial years and assumptions about the composition of greenhouse gas emissions (Tebaldi et al. 2021).

The ensemble of CMIP6 models projects greater and somewhat faster warming than CMIP5 models (Forster et al. 2021). For example, in the CMIP6 ensemble, average global surface air temperature is projected to increase by 4.4°C (7.9°F) by 2081–2100 relative to 1986–2005 under SSP5-8.5, compared to the CMIP5 ensemble average increase of 3.7°C (6.7°F) under RCP 8.5 (Tebaldi et al. 2021). In addition, CMIP6 models project that certain global warming levels (e.g., 1.5°C [2.7°F], 2°C [3.6°F]) will be reached three to nine years earlier than projected by CMIP5 models (Tebaldi et al. 2021). To illustrate, 2°C of warming above the 1850–1900 average temperature is projected to occur in 2038 under SSP5-8.5 and 2041 under RCP 8.5 (Tebaldi et al. 2021). The greater warming of CMIP6 models has been attributed to the inclusion of some models with unrealistically high ECSs that overestimated observed warming (Forster et al. 2021, Tebaldi et al. 2021). Constraining future warming projections by the observed warming trend effectively eliminates many of the unreliable models (Tokarska et al. 2020) and brings CMIP6 temperature projections closer to those of CMIP5 (Tebaldi et al. 2021). For example, when the observed warming trend is used to constrain future warming projections for both CMIP5 and CMIP6 models, the ensemble average increase in temperature by 2081–2100 is 3.5°C (6.2°F) and 3.6°C (6.5°F), respectively (Tebaldi et al. 2021).

In both CMIP6 and CMIP5 models, high latitudes warm more than low latitudes, particularly in the Northern Hemisphere, and continents warm more than oceans (Tebaldi et al. 2021). Projected changes in global precipitation, including spatial patterns, are also similar in CMIP6 and CMIP5 (Lee

et al. 2021, Tebaldi et al. 2021). In both sets of results, the largest increases in precipitation occur in the equatorial Pacific and at the poles, and drying trends are most pronounced in the Mediterranean, Central America, Amazonia, southern Africa, and western Australia (Tebaldi et al. 2021).

In the western United States, the spatial pattern of changes in temperature and precipitation projected by CMIP5 and CMIP6 models is similar (Almarzroui et al. 2021). Although CMIP6 projects higher average temperatures than CMIP5, the range of temperature and precipitation projections over the United States and Canada is smaller in CMIP6 (Martel et al. 2022). Of the 21 CMIP6 models used, seven had ECS >4°C (one with ECS >5°C) and two had ECS <2°C (Zelinka et al. 2020, Martel et al. 2022). However, CMIP6 projects greater increases in temperature and precipitation extremes than CMIP5 (Chen et al. 2020). Of the 11 CMIP6 models used, three had ECS >4°C (one with ECS >5°C) and one had ECS <2°C (Chen et al. 2020, Zelinka et al. 2020). CMIP6 models also project declines in wind power density (a measure of the wind energy available in a given location) in much of the United States and Canada, whereas CMIP5 models project little to no change (Martinez and Iglesias 2022). Of the 18 CMIP6 models used, six had ECS >4°C (one with ECS >5°C) and two had ECS <2°C (Zelinka et al. 2020, Martinez and Iglesias 2022).

In CMIP6 models, the area covered by snow during spring (April–June) is projected to decline throughout the twenty-first century under SSP1-2.6, 2-4.5, 4-6.0, and 5-8.5, as it was under all RCPs in CMIP5 models. Declines in snow cover stabilized by the end of the century only under SSP1-2.6 (Mudryk et al. 2020, Zhu et al. 2021). Under SSP5-8.5, spring snow cover in the Northern Hemisphere from 2081–2100 is projected to be 40 percent lower than from 1995–2014 (Zhu et al. 2021). However, given that seven of the 20 CMIP6 models that resulted in the latter projection had ECS >4°C, and three of those had ECS >5°C (Zelinka et al. 2020, Zhu et al. 2021), projected declines in snow cover may be exaggerated. By contrast, CMIP5 projections under RCP 8.5 projected spring snow cover from 2080–2099 that was 25 percent lower than that from 1986–2005 (Brutel-Vuilmet et al. 2013). Projected annual mean streamflow over the Northwest is marginally greater in CMIP6 models than CMIP5 models (Martel et al. 2022).

A suite of nine crop models projected a larger decrease in median global crop yields by the end of the twenty-first century when using CMIP6 model outputs than CMIP5 model outputs (-19 to 1 percent in CMIP6 versus -13 to 5 percent in CMIP5) (Muller et al. 2021). This may result from a warmer growing season in the CMIP6 model ensemble, which in turn reflects the inclusion of several CMIP6 models with ECS >5°C (Zelinka et al. 2020, Muller et al. 2021). In general, projected global crop yield increased until mid-century and then declined. Muller et al. (2021) did not account for temperature-driven changes in growing season length.

CMIP6 models overestimate global mean leaf area index to a greater extent than CMIP5 models (Song et al. 2021). The leaf area index, the ratio of the one-sided leaf area per unit ground area, is associated with primary productivity, carbon balance, and water and nutrient budgets. Overestimation of the index leads to overestimating primary production, transpiration, and evaporation from the canopy (Song et al. 2021). Furthermore, in temperate regions, CMIP6 models overestimate tree height, which may lead to overestimating aboveground carbon storage and underestimating wind speed (Song et al. 2021). However, in both CMIP5 and CMIP6 models, leaf area index is projected to increase in virtually all biomes worldwide under scenarios of 1.5°C and 2°C warming above pre-industrial levels (Peng et al. 2022).

Use of CMIP6 Projections in Climate Impacts Assessments

Best practices for analyzing and reporting projections of future climate from CMIP5 and earlier generations of climate models were to calculate the average and range across at least ten climate models (Mote et al. 2011). This approach assumed that each model was an independent and equally valid representation of the Earth system. Neither of these assumptions are met within the CMIP6 ensemble. The climate models within the CMIP5 ensemble are not independent, either, often because a given team produced more than one model, such as an early GCM and a subsequent ESM (Knutti et al. 2013, Eyring et al. 2019). Consequently, different models may share code or even submodels that represent major processes (Table 2), violating the assumption of independence (Knutti et al. 2013). Model independence can be evaluated by testing whether model errors are correlated. The effective number of independent models is much less than the total number of models in the ensemble (Eyring et al. 2019). Because several fundamental biogeochemical processes are represented by the same algorithm in most models, selecting climate models from different institutions is a useful but imperfect surrogate for selecting independent models.

The ensemble of climate models from CMIP5 appear to be equally valid representations of Earth's system given their good agreement with observations (Knutti et al. 2013) and range of ECSs (Hausfather et al. 2022). Selecting a subset of models that best simulate past climate of a particular region (e.g., Rupp et al. 2013) also can increase the probability that those models are equally valid for a given application. As explained above, in contrast to the CMIP5 models, not all CMIP6 models can be considered equally valid (Eyring et al. 2019, Torkarska et al. 2020, Hausfather et al. 2022).

The IPCC's correction method of weighting modeled temperature increases is useful in some contexts, but may be impractical when evaluating climate projections at a regional or local level (Eyring et al. 2019). Instead, two alternative approaches have been recommended. First, projections can be presented in terms of temperature increase instead of time. For example, one can consider how other aspects of Oregon's climate are projected to respond to 2°C of global warming regardless of the year in which 2°C warming is reached. This approach is consistent with the Paris Agreement's target levels of global warming. However, time-based estimates are often necessary for impacts assessments (Hausfather et al. 2022). Second, one can select a subset of CMIP6 models with ECSs within the IPCC's likely assessed range (Hausfather et al. 2022). It remains best practice to analyze and present an average and range of projections from at least ten global climate models with realistic ECSs that simulate the historical climate well (Mote et al. 2011, Hausfather et al. 2022).

Availability of CMIP6 Downscaled Projections and Applications to Impact Assessments

Local and regional climate impacts assessments often rely on downscaled climate projections. There are two types of downscaling, statistical and dynamical. Statistical downscaling uses statistical relations between historical, fine-resolution observations of weather (e.g., daily) or climate (e.g., monthly) and coarse-resolution global climate model outputs to increase the spatial resolution of climate projections. Statistical methods attempt to correct global climate model biases under the assumption that historical biases also will be applicable in the future (the stationarity assumption). Dynamical downscaling increases the resolution of climate projections by applying numerical, three-dimensional representations of atmospheric hydrodynamics and thermodynamics. These representations are similar to those used in global climate models, but have finer resolution and are not run over the entire globe. The regional climate models used in dynamical downscaling, however, use global climate model results at their geographic boundaries, and therefore include all of the

Table 2. Coupled general circulation models (GCMs) and Earth system models (ESMs) that participated in ScenarioMIP, adapted from Table AII.5 in Gutiérrez and Tréguier 2021. Models are grouped by the land surface model and processes they included. Aerosols are prescribed or emissions-driven. Land carbon, active land carbon cycle; N cycle, active nitrogen cycle; prog veg, prognostic biogeography of vegetation; permafrost, carbon included in a permafrost pool; fires, dynamic fires. Equilibrium climate sensitivity (ECS) values in Celsius (°C) from Zelinka et al. 2020, updated at github.com/mzelinka/cmip56_forcing_feedback_ecs/blob/master/CMIP6_ECS_ERF_fbks.txt.

GCM or ESM	References	ECS (°C)	Atmosphere model	Aerosol model	Atmospheric chemistry model	Ocean model	Cryosphere model	Land surface model	Land processes	Ocean interactive biochemistry model
TaiESM1.0	W.-L. Lee et al. 2020	4.36	TaIAM1	SNAP, emissions-driven	none	POP2	CICE4.0	CLM4.0	land carbon, N cycle, fires	none
FIO-ESM-2-0	Bao et al. 2020	Not evaluated	CAM5	MACv2-SP, prescribed	none	POP-W with MASNUM surface wave model	CICE4.0	CLM4.0	land carbon, N cycle	BEC
CMCC-CM2-SR5, CMCC-ESM2	Cherchi et al. 2019	3.55, 3.58	CAM5.3	MAM3, emissions-driven	specified oxidants based on MOZART simulations	NEMO3.6	CICE4.0	CLM4.5	land carbon, N cycle, permafrost, fires	CM2-SR5: none; ESM2: BFM5.2
FGOALS-f3-L	He et al. 2020	2.98	FAMIL 2.2	prescribed	none	LICOM3.0	CICE4.0	CLM4.0 / CAS-LSM	none	none
FGOALS-g3	Li et al. 2020	2.87	GAMIL3	prescribed	none	LICOM3.0	CICE4.0	CLM4.0 / CAS-LSM	none	none
NorESM2-LM, NorESM2-MM	Seland et al. 2020	2.56, 2.49	CAM6-Nor2	OsloAero6, emissions-driven	OsloAero6: prescribed oxidants, interactive sulphur chemistry, SOA precursor chemistry	BLOM1.0	CICE5.1	CLM5	land carbon, N cycle, permafrost, fires	HAMOCC5.1
CESM2, CESM2-FV2, CESM2-WACCM	Danabasoglu et al. 2020	5.15, 5.16, 4.68	CAM6	MAM4, emissions-driven	CESM2: prescribed oxidants; others: interactive	POP2	CICE5.1, CISM2.1	CLM5	land carbon, N cycle, permafrost, fires	MARBL
AWI-CM-1-1-MR	Sidorenko et al. 2015, Semmler et al. 2020	3.16	ECHAM6.3.04p1	MACv2 SP, prescribed	none	FESOM 1.4	FESOM 1.4	JSBACH3.20	none	none

MPI-ESM-1-2-HAM	Neubauer et al. 2019	2.95	ECHAM6.3	HAM2.3, emissions-driven	specified oxidants, sulphur chemistry	MPIOM 1.63	MPIOM 1.63	JSBACH3.20	land carbon, N cycle, prog veg, fires	HAMOCC6
MPI-ESM1-2-LR, MPI-ESM1-2-HR	Müller et al. 2018, Mauritsen et al. 2019	MPI-ESM1-2-LR: 3.03, MPI-ESM1-2-HR: 2.98	ECHAM6.3	MACv2-SP, prescribed	none	MPIOM 1.63	MPIOM 1.63	JSBACH3.20	LR: land carbon, N cycle, prog veg, fires; HR: none	HAMOCC6
NESM3	Cao et al. 2018	4.76	ECHAM v6.3	prescribed	none	NEMO v3.4	CICE 4.1	JSBACH v3.1	land carbon, prog veg	none
KIOST-ESM	Pak et al. 2021	Not evaluated	GFDL-AM2.0	GFDL-AM2.0, emissions-driven	none	GFDL-MOM5.0	GFDL-SIS	GFDL-LM3.0	land carbon, N cycle, prog veg	TOPAZ2
GFDL-CM4	Held et al. 2019	3.89	GFDL-AM4.0.1	GFDL-AM4.0.1, emissions-driven	GFDL-AM4.0.1: specified oxidants, fast chemistry, aerosol only	GFDL-OM4p25 (GFDL-MOM6)	GFDL-SIM4p25	GFDL-LM4.0.1	land carbon, prog veg, fires	GFDL-BLINGv2
GFDL-ESM4	Dunne et al. 2020	2.65	GFDL-AM4.1	GFDL-AM4.1, emissions-driven	GFDL-ATMCHEM4.1, interactive	GFDL-OM4p5 (GFDL-MOM6)	GFDL-SIM4p5	GFDL-LM4.1	land carbon, prog veg, fires	GFDL-COBALTv2
HADGEM3-GC31-LL, HADGEM3-GC31-MM	Kuhlbrodt et al. 2018, Williams et al. 2018, Sellar et al. 2019	5.55, 5.44	MetUM-HadGEM3-GA7.1	UK-GLOMAP, emissions-driven	none	NEMO-HadGEM3-GO6.0	CICE-HadGEM3-GSI8	JULES-HadGEM3-GL7.1	none	none
UK-ESM1.0-LL, UK-ESM1.1-LL	Sellar et al. 2019, Mulcahy et al. in review	ESM1.0: 5.36; ESM1.1: 5.27	MetUM-HadGEM3-GA7.1	UK-GLOMAP, emissions-driven	UKCA-StratTrop	NEMO-HadGEM3-GO6.0	CICE-HadGEM3-GSI8	JULES-HadGEM3-GL7.1, TRIFFID, RothC	land carbon, N cycle, prog veg	MEDUSA2
KACE-1-0-G	J. Lee et al. 2020	4.75	MetUM-HadGEM3-GA7.1	UKCA-GLOMAP-mode, emissions-driven	specified oxidants for aerosols	MOM4p1	CICE-HadGEM3-GSI8	JULES-HadGEM3-GL7.1	none	none
IPSL-CM6A-LR	Boucher et al. 2020	4.7	LMDZ NPv6	prescribed	specified oxidants for aerosols	NEMO3.6	NEMO-LIM3	ORCHIDEE (v2.0, water / carbon / energy mode)	none	PISCES

IPSL-CM5A2-INCA		3.82	LMDZ APv5	INCA, emissions driven	INCA, interactive	NEMO3.6	NEMO-LIM3	ORCHIDEE (IPSLCM5A2.1, water / carbon / energy mode)	land carbon	PISCES
CNRM-CM6-1, CNRM-CM6-1-HR	Voldoire et al. 2019, Saint-Martin et al. 2021	4.9, 4.33	Arpege 6.3	TACTIC_v2, prescribed	OZL_V2, linear ozone	NEMO3.6	Gelato 6.1	ISBA-CTRIP	none	none
CNRM-ESM2-1	Seferian et al. 2019	4.79	Arpege 6.3	TACTIC_v2, emissions-driven	REPROBUS-C-V2	NEMO3.6	Gelato 6.1	ISBA-CTRIP	land carbon, fires	Pisces 2.s
ACCESS-ESM1-5	Ziehn et al. 2020	3.88	HadGAM2 r1.1	CLASSIC (v1.0), emissions-driven	specified oxidants for aerosols	ACCESS-OM2 GFDL-MOM5	CICE4.1	CABLE2.4	land carbon, N cycle	Wombat1.0
ACCESS-CM2	Bi et al. 2020	4.66	HadGEM3-GA7.1	UKCA-GLOMAP-mode, emissions-driven	specified oxidants for aerosols	ACCESS-OM2 GFDL-MOM5	CICE5.1.2	CABLE2.5	none	none
EC-Earth3, EC-Earth3-LR; options: AerChem, Veg	Döscher et al. 2021	EC-Earth3: 4.26; EC-Earth3-AerChem: 3.87; EC-Earth3-Veg: 4.33; EC-Earth3-Veg-LR: 4.23	IFS cy36r4	EC-Earth3: MACv2-SP, prescribed; AerChem: TM5, emissions-driven	EC-Earth3: none; AerChem: interactive	NEMO3.6	LIM3	EC-Earth3: H-TESSEL; Veg: H-TESSEL, LPJ-GUESS	EC-Earth3: none; Veg: N cycle, prog veg, fires	none
EC-Earth3-CC	Döscher et al. 2021	4.23	IFS cy36r4	MACv2-SP, prescribed	none	NEMO3.6	LIM3	H-TESSEL, LPJ-GUESS	land carbon, N cycle, prog veg, fires	PISCES v2
CAMS-CSM1-0	Rong et al. 2018	2.29	ECHAM5_CAMS	MACv2-SP, prescribed	none	MOM4	SIS1	CoLM	none	none
CAS-ESM 2	Zhang et al. 2020	3.51 (Schlund et al. 2020)	IAP AGCM 5.0	MAM3, MOZART	IAP-AACM	LICOM 2.0	CICE4.0	CoLM	Land carbon, prog veg, fires	none

BCC-CSM2-MR	Wu et al. 2019	3.02	AGCM3	MACv2-SP, prescribed	none	MOM4	SIS1	BCC_AVIM2	none	none
CanESM5, CanESM5-CanOE	Swart et al. 2019	CanESM5: 5.64	CanAM5	emissions-driven	specified oxidants, interactive sulphur	NEMO3.4.1	LIM2	physics, CLASS3.6 biogeochemistry, CTEM1.2	land carbon	CanESM5: CMOC; CanESM5-CanOE: CanOE
IITM-ESM	Swapna et al. 2018	2.37	IITM-GFS	MAC-v2, prescribed	none	MOM4p1	SISv1.0	NOAH LSMv2.7.1	none	TOPAZv2.0
E3SM 1.0, E3SM-1-1, E3SM-1-1-ECA	Golaz et al. 2019	E3SM-1-0: 5.31	E3M v1.0	MAM4, emissions-driven	specified oxidants for aerosols; linear interactive stratospheric ozone (LINOZ v2)	MPAS-Ocean v6.0	MPAS-Seaice v6.0	ELM v1.0, based on CLM4.5	E3SM 1.0: none; E3SM1.1: land carbon, N cycle, fires	none
INM-CM4-8, INM-CM5-0	Volodin et al. 2017, 2018	1.83; 1.92	CM4: INM-AM4-8; CM5: INM-AM5.0	INM-AER1, emissions-driven	none	INM-OM5	INM-ICE1	INM-LND1	land carbon	none
MIROC-ES2L, MIROC6	Tatebe et al. 2019, Kawamiya et al. 2020	MIROC-ES2L: 2.66; MIROC6: 2.6	CCSR AGCM	SPRINTARS, emissions-driven	MIROC-ES2L and MIROC6: prescribed oxidants	COCO4.9	COCO4.9	MIROC6: MATSIRO6.0; MIROC-ES2L: MATSIRO6.0 with visit-e v1.0	MIROC6: none; MIROC-ES2L: land carbon, N cycle	OECO v2.0
MRI-ESM-2.0	Mizuta et al. 2012, Yukimoto et al. 2019	3.13	MRI-AGCM3.5	MASINGAR mk-2r4c, emissions-driven	MRI-CCM2.1, interactive	MRI.COM4.4	MRI.COM4.4	HAL 1.0 and MRI-LCCM2	land carbon, prog veg, fires	MRI.COM4.4
GISS-E2-1-G, GISS-E2-1-H, GISS-E2.1-G-CC, GISS-E2-2-G	Kelley et al. 2020, Rind et al. 2020	GISS-E2-1-G: 2.71; GISS-E2-1-H: 3.12; GISS-E2-2-G: 2.43	GISS-E2-1: GISS-E2.1; GISS-E2-2-G: GISS-E2-2	Varies with physics. Versions p1, p3: OMA. Version p5: MATRIX.	Varies with physics. Version p1: none. Version p3, p5: GPUCCINI, interactive.	GISS-E2-1-G, GISS-E2-2-G: GISS ocean; GISS-E2-1-H: HYCOM	GISS-SI	GISS-LSM	none	GISS-E2-1-G-CC: NOBM; others: none
CIESM	Lin et al. 2020	5.63	CIESM-AM	MACv2-SP, prescribed	none	CIESM-OM	CICE4	CIESM-LM	none	none
MCM-UA-1-0	Delworth et al. 2002	3.65 (Schlund et al. 2020)	Manabe R30L14	none	none	MOM1.0	thermo-dynamic simplified sea ice	Manabe bucket scheme	none	none

global models' biases. The projections derived from dynamical downscaling may be more accurate than those from statistically downscaling because they directly incorporate fine-resolution data rather than statistically approximating fine-resolution data from coarse-resolution data. However, such improvement in accuracy depends on the availability of fine-resolution data within the full extent of the model, which is rare.

Dynamically downscaled data still may have substantial biases. Several sets of statistically or dynamically downscaled CMIP6 projections are available or in preparation (Table 3). Many of these products were generated with methods that were applied to CMIP5 models, and still are widely used in assessments of the impacts of climate change (Kim et al. 2022). Each product was created with a different method, spatial and temporal resolution, and observational data. The reference data used to correct the future projections were a main cause of differences among downscaled climate projections for the northwestern United States (Jiang et al. 2018). However, the bias correction method and the downscaling algorithm used in each method are the most obvious causes of divergence among downscaled projections. The choice of GCM realization (a model run with a given set of initial conditions or parameters) strongly affects divergence among projections, with or without downscaling, at the extent of the conterminous United States (Kim et al. 2022).

The scientific community is evaluating CMIP6 projections of a range of climate variables, and the resulting effects on biogeochemical and hydrological cycles, at global to local extents. The realism of emissions pathways and their radiative forcing remains uncertain because these depend on social and economic decisions. Simulated responses of planetary processes to forcing is driven in part by the coarse-resolution concentrations of anthropogenic aerosols that are fed into ESMs (Persad et al. 2022). Uncertainty in values of these concentrations to 2050 and beyond, which may exceed the increases in values since 1850 (Wilcox et al. in review), causes differences in radiative forcings, from -0.3 to -1.5 W m^{-2}, among models results. Consequently, most of the literature on climate impacts relevant to Oregon and the Northwest is still based on CMIP5 (e.g., Dalton and Fleishman 2021); little is based on CMIP6 or has compared outcomes that were based on the two sets of models. This will change in the coming years as CMIP6 projections become better understood and more accessible, and as their biases are corrected. Some downscaled CMIP6 projections are already available, and additional downscaled projections are in production. Climate impacts assessments that incorporated projections of future climate from CMIP5 are still valid and useful. It may be worth considering whether to update the assessments, or compare inferences based on CMIP5 and CMIP6, in a few years as new climate data emerge and model weaknesses are addressed.

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Table 3. Sources and attributes of downscaled CMIP6 climate projections.

Product	Method	Spatial resolution and domain	References	Status
Statistical				
NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)	Statistical: bias-correction spatial disaggregation (BCSD)	25 km; global	Thrasher et al. 2022 Technical documentation: www.nccs.nasa.gov/sites/default/files/NEX-GDDP-CMIP6-Tech_Note.pdf Data: ds.nccs.nasa.gov/thredds2/catalog/AMES/NEX/GDDP-CMIP6/catalog.html	Available
LOCA2	Statistical: localized constructed analogs (LOCA)	6 km; conterminous United States	Overview: loca.ucsd.edu	Available
Global Downscaled Projections for Climate Impacts Research	Statistical: quantile delta mapping and quantile-preserving localized-analog downscaling	25 km; global	Overview: planetarycomputer.microsoft.com/dataset/group/cil-gdpcir Data access: /github.com/ClimateImpactLab/downscaleCMIP6	Available
CarbonPlan	Statistical: four different methods	25 km; global	Chegwidden et al. 2022 carbonplan.org/research/cmip6-downscaling-explainer	Available
WorldClim	Statistical: bias correction	Various; global	www.worldclim.org/data/cmip6/cmip6climate.html	Available
ClimateNA	Statistical: Delta change	1 km; North America	adaptwest.databasin.org/pages/adaptwest-climatena	Available
MACAv3	Statistical: multivariate adaptive constructed analogs (MACA)	4 km; conterminous United States	Overview: www.climatologylab.org/maca.html	In progress
Dynamical				
CMIP6 downscaling with WRF	Dynamical: weather research and forecasting (WRF) regional model	9 km; western United States	dept.atmos.ucla.edu/alexhall/downscaling-cmip6	Available
North American CORDEX	Dynamical	25–50 km; North America	Overview: na-cordex.org/index.html	In progress

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Extreme Temperatures

Larry O'Neill, Nicholas Siler, Paul Loikith, and Alexis Arends

Periods of unusually hot or cold weather, or extreme temperature, can have substantial and detrimental impacts on individuals, communities, infrastructure, agriculture, and other sectors. More high-temperature records than low-temperature records were broken during the last two decades at long-term monitoring stations within Oregon (Table 1). This trend is consistent with the observed effects of climate change (Meehl et al. 2009). Temperatures in Pendleton are an exception to the trend; since the 1980s, Pendleton has broken more low-temperature records than high-temperature records. Here, we summarize observed variability and trends in extreme warm and cold temperatures in Oregon and discuss projected changes in heat and cold waves in the coming decades.

Decade	Astoria	Portland	Salem	Eugene	The Dalles	Pendleton	Ontario	Medford
1951–1960	0.36	0.56	1.29	0.75	4.89	1.08	1.02	1.30
1961–1970	0.45	0.87	0.97	1.48	0.43	1.26	1.36	0.85
1971–1980	0.33	1.31	0.77	0.74	0.29	2.06	0.72	0.85
1981–1990	0.58	2.08	0.83	0.76	1.80	0.63	0.70	3.71
1991–2000	2.08	5.64	6.80	1.10	1.04	0.57	1.23	4.00
2001–2010	4.00	4.54	8.50	1.00	0.76	0.83	5.25	8.00
2011–2020	2.53	3.29	11.0	2.94	1.38	0.58	1.48	9.20

Table 1. Ratio of the number of new daily record high to record low temperatures per decade at selected long-term climate monitoring stations in Oregon. A ratio greater than 1 indicates that more record highs than record lows were set. A ratio of 2, for instance, indicates that two new record highs occurred for every one new record low. National Oceanic and Atmospheric Administration / National Centers for Environmental Information Global Historical Climatology Network daily data (NOAA/NCEI GHCNd, Menne et al. 2012) via the Iowa Environmental Mesonet portal (mesonet.agron.iastate.edu).

Extreme Heat

Heat is the leading cause of weather-related deaths in the United States, killing approximately 1500 people per year from 2008 through 2017 (Khatana et al. 2022). Although dangerously warm temperatures are less common in Oregon than in many other parts of the country, Oregonians are less likely than residents of most other states to have air conditioners in their homes, leaving them more vulnerable to high heat. To illustrate, in June 2021, record-breaking heat caused an estimated 116 deaths across the state, mostly inside homes without air conditioning.

Dangerous heat is almost always associated with a weather event called a heat wave (Peterson et al. 2013). There is no single definition of a heat wave, but heat waves usually are defined with respect to both the relative magnitude of temperature anomalies (e.g., temperatures above the 99th percentile for a given location and season) and the duration of those anomalies (e.g., at least three consecutive days). By this definition, a prolonged period with temperatures exceeding 100°F (38°C) would not be considered a heat wave if it occurred in Phoenix, Arizona, in July, but would be considered a heat wave if it occurred in Portland in July or in Phoenix in March. Heat waves can occur during any season, although the term heat wave is generally reserved for prolonged stretches of extreme heat that pose a substantial health and safety risk. Here, we focus on summer (June–September), when temperatures in Oregon are most likely to be dangerously high.

Previous studies of heat-wave trends distinguished between extremely warm daytime high temperatures and overnight low temperatures (Bumbaco et al. 2013). Although extremely warm

daytime highs often generate the most press coverage and public interest, extremely warm overnight lows often are a greater threat to human health, especially where access to air conditioning is limited (Gershunov et al. 2011). In 2021, in response to the increasing vulnerability of marginalized populations to the warming climate, the Oregon legislature directed funding to the Oregon Health Authority to distribute air conditioning units to eligible people at risk for heat-related illness.

Observed Trends in Extreme Daytime Heat

Extreme warm temperatures often are defined on the basis of absolute thresholds. A common definition of an extremely warm day in the Pacific Northwest is a day on which the maximum temperature is 90°F (32°C) or above. By this definition, the number of extremely warm days increased significantly across Oregon since 1951 (linear regression; >95% probability that the result was not obtained by chance alone). The number of extremely warm days increased significantly in Portland, Pendleton, and Medford since 1940 (Figure 1). Portland, for instance, averaged 7.4 days ≥90°F per year during the 1950s and 17.3 in the 2010s. From 2011–2020, the number of days ≥90°F at many long-term climate monitoring stations in Oregon was significantly greater than the average from 1951–2020 (Table 2). Moreover, 2021 and 2022 were among the hottest years on record in the state as measured by days above 90°F (Table 2). In Portland, 24 days in 2021 and 29 days in 2022 were above 90°F, well above the 1951–2020 average of 12.5 days per year (Table 2). The number of extremely warm days in these years ranked fourth and second, respectively, in Portland's historical record, ahead of the 31 days recorded during 2018.

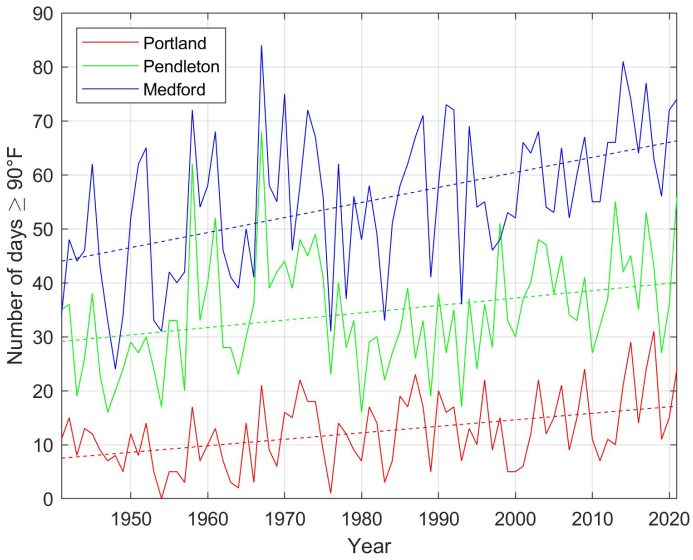

Figure 1. Number of days per year on which the observed daily high temperature was 90°F (32°C) or above. Dashed lines are statistically significant linear regressions. Data source: NOAA/NCEI GHCNd.

Years	Astoria	Portland	Salem	Eugene	The Dalles	Pendleton	Ontario	Medford
1951–1960	0.6	7.4	14.8	13.6	29.5	31.9	50.0	53.5
1961–1970	0.3	9.4	17.4	16.5	37.3	39.0	53.7	55.7
1971–1980	0.5	12.5	16.0	16.0	42.0	36.2	49.3	53.3
1981–1990	0.3	14.2	16.5	15.5	39.6	29.4	51.4	54.8
1991–2000	0.3	11.9	15.6	14.8	43.2	31.8	49.3	55.8
2001–2010	1.1	14.7	17.8	17.4	39.9	39.0	56.8	60.4
2011–2020	0.8	17.3	21.5	21.7	44.1	40.5	54.1	67.4
1951–2020 average	0.6	12.5	17.1	16.5	39.4	35.4	51.7	55.8
2021–2022	1.0	27	37	38	65	56	66	77

Table 2. Average number of days per year on which the observed daily high temperature at long-term monitoring stations in Oregon was 90°F (32°C) or above. Data source: NOAA/NCEI GHCNd.

Observed Trends in Extreme Nighttime Heat

The number of extremely warm nights is also increasing across Oregon. A common absolute threshold for nighttime extreme heat is a day on which the minimum temperature is 65°F (18°C) or above. In western Oregon, such warm nights were rare before 1990 (Table 3, Figure 2), but the number of warm nights has increased significantly in Portland, Medford, The Dalles, and Ontario in the past two decades. In Pendleton, by contrast, extremely warm nights were more common before about 2000 than they are now, and the annual number of extremely warm nights has not changed significantly since 1940 (Table 3, Figure 2). Extremely warm nights are rare in Salem and Eugene, even since 2011 (Figure 3). Similar to the trends in the number of extremely warm days, several long-term climate monitoring stations in Oregon recorded significantly more extremely warm nights from 2011–2020 than from 1951–2020 (Table 3). The exceptions were Astoria, Eugene, and Salem. The number of extremely warm nights in 2021–2022 was far above the historical number (Table 3).

Years	Astoria	Portland	Salem	Eugene	The Dalles	Pendleton	Ontario	Medford
1951–1960	0.0	0.2	0.0	0.0	6.8	9.5	6.6	1.0
1961–1970	0.0	0.1	0.0	0.0	13.4	9.6	7.1	1.7
1971–1980	0.0	1.6	0.1	0.0	14.3	10.7	7.5	1.4
1981–1990	0.0	1.4	0.0	0.1	14.9	7.2	5.7	1.8
1991–2000	0.0	2.7	0.2	0.1	14.8	5.9	3.9	3.9
2001–2010	0.0	2.3	0.8	0.2	15.8	6.4	10.2	6.6
2011–2020	0.0	5.2	1.2	0.0	20.9	6.0	8.9	11.4
1951–2020 average	0.0	1.9	0.3	0.1	14.4	7.9	7.1	4.0
2021–2022	0.0	17	6	3	43	19	33	26

Table 3. Average number of days per year on which the observed daily minimum temperature at long-term monitoring stations in Oregon was 65°F (18°C) or above. Data from NOAA/NCEI GHCNd.

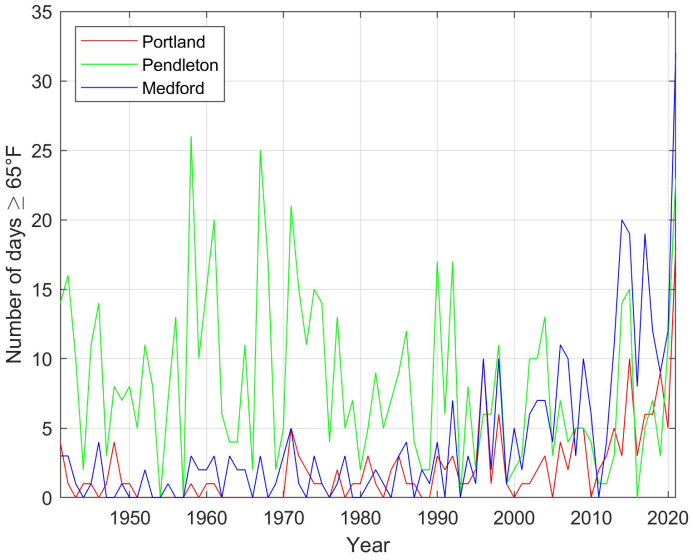

Figure 2. Number of days per year on which the observed daily low temperature was 65°F (18°C) or above. Linear trends during this period were not statistically significant. Data source: NOAA/NCEI GHCNd.

Days Below Freezing

At many locations across Oregon, including Portland and Medford, the annual number of days on which the minimum temperature is below freezing (32°F or 0°C) has decreased significantly since 1940 (Figure 4). However, trends in the observed number of cold days are less consistent than trends in the number of warm days. For example, the number of sub-freezing days in Astoria, Eugene, and Pendleton has not changed significantly (Table 4). Nevertheless, at all stations except Pendleton, fewer days per year were below freezing in 2021 and 2022 than the annual average from 1951–2020 (Table 4).

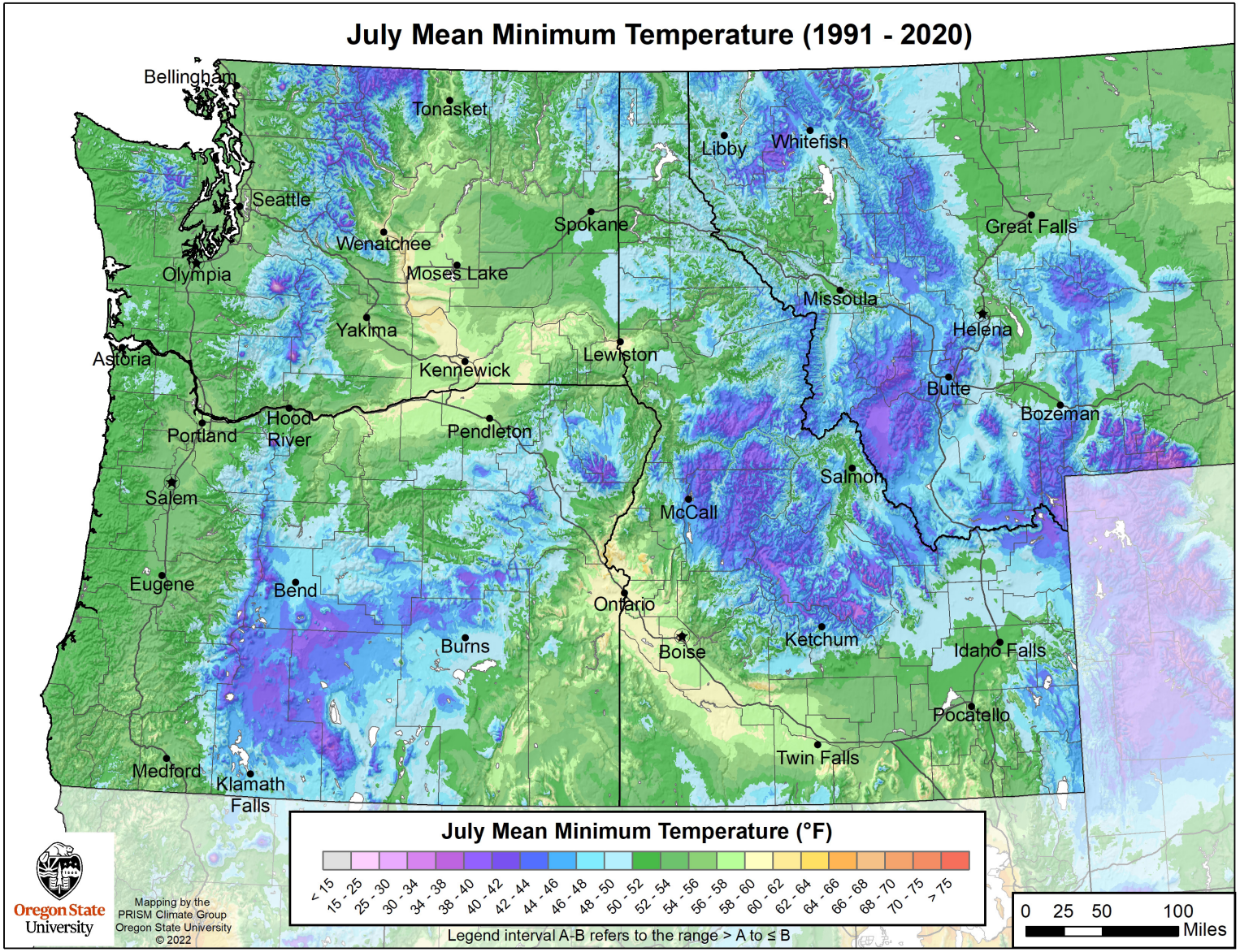

Figure 3. Average minimum July temperatures across the Northwest, 1990–2020.

Extreme Heat, Public Health, and Workplace Safety

During May 2022, the Oregon Occupational Safety and Health Administration (OSHA) adopted new regulations on workplace heat exposure (OOSH 2022). These regulations are based on thresholds of the heat index. The heat index, also known as the apparent temperature, is what the temperature feels like to the human body when relative humidity is combined with air temperature. As air becomes more humid, the human body is less able to cool through the evaporation of perspiration. Therefore, the incidence of heat illness is not necessarily directly correlated with air temperature. When relative humidity is low, the heat index is roughly the same as, or slightly cooler than, the air temperature. As relative humidity increases, the heat index becomes higher than the air temperature, and the difference between the heat index and the air temperature increases. For example, when the air temperature is 90°F (32°C), the heat index will be 88°F (31°C) if the relative humidity is 30 percent, but 100°F (38°C) if the relative humidity is 60 percent. To combat heat illness, the Oregon OSHA guidelines stipulate that when the heat index is 90°F or above, employers must provide each employee with a break of at least 10 minutes every two hours, and at least one quart of drinking water per hour.

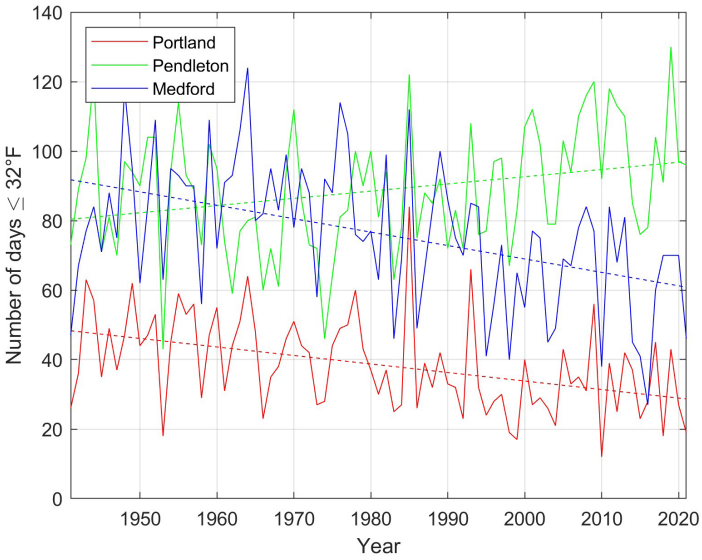

Figure 4. Number of days per year on which the observed daily low temperature was 32°F (0°C) or below. Dashed lines are linear regressions. Data source: NOAA/NCEI GHCNd.

Years	Astoria	Portland	Salem	Eugene	The Dalles	Pendleton	Ontario	Medford
1951–1960	27.5	46.2	63.6	57.9	87.1	91.1	142.5	86.1
1961–1970	39.8	43.1	67.0	42.9	77.8	77.0	141.2	93.1
1971–1980	35.5	42.4	67.7	57.0	76.5	79.5	137.5	86.7
1981–1990	36.7	37.5	63.4	57.2	72.1	85.0	145.5	77.3
1991–2000	28.6	31.1	48.6	48.5	66.5	86.8	132.0	64.4
2001–2010	27.9	31.3	53.0	53.1	74.6	100.7	119.3	65.9
2011–2020	30.7	32.7	46.9	54.0	73.9	100.2	111.3	61.6
1951–2020 average	32.4	37.8	58.6	52.9	75.5	88.6	132.7	76.4
2021–2022	31.5	19.0	38.5	39.0	82.0	87.0	120.0	52.0

Table 4. Average number of days per year on which the observed daily minimum temperature at long-term monitoring stations in Oregon was 32°F (0°C) or below. Data from NOAA/NCEI GHCNd.

Historically, heat waves across Oregon rarely were humid (Rastogi et al. 2020). Because high heat and low relative humidity tend to co-occur in Oregon, the heat index is generally a few degrees lower than the actual air temperature. As a result, approximating the heat index with only air temperature would significantly overestimate the number of high heat-index days in Oregon.

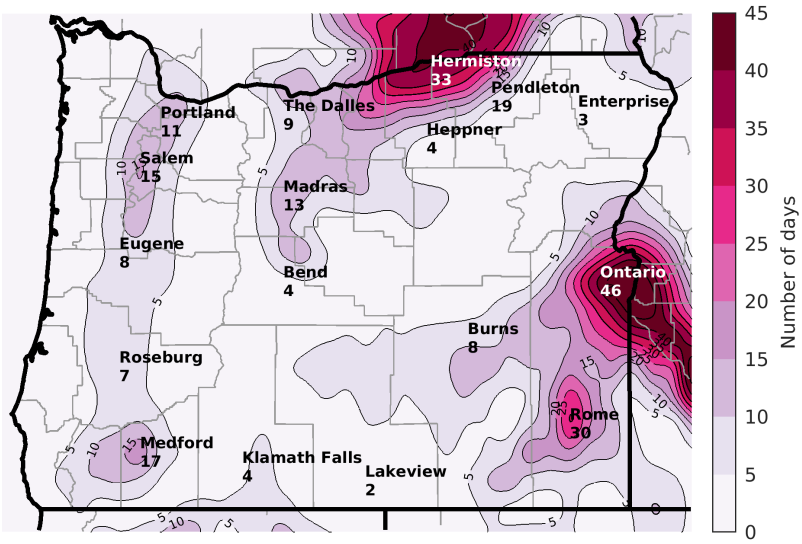

Figure 5. Average annual number of days from 1991–2020 on which the heat index was 90°F (32°C) or above. Heat indexes derived from ERA5 atmospheric reanalysis data.

The occurrence of high heat-index days varies considerably across Oregon (Figure 5). In western Oregon from 1991–2020, the greatest number of days per year with a heat index above 90°F occurred in the Willamette Valley and Rogue Valley, ranging from an average of 17 days in Medford to 7 days in Roseburg. In much of Oregon east of the Cascades, the heat index exceeded 90°F on fewer than 10 days per year. However, the heat index exceeded 90°F in Ontario and Rome (Malheur County) on an average of 46 and 30 days per year, respectively. In northeastern Oregon, the heat index exceeded 90°F in Hermiston and Pendleton on an average of 33 and 19 days per year, respectively.

The summer of 2021 was the warmest in Oregon's recorded history. Heat indexes exceeded 90°F on many more days (Figure 6) than the most recent 30-year average (Figure 5). Summer heat conditions similar to those in 2021 are projected to become more common by the middle to end of this century.

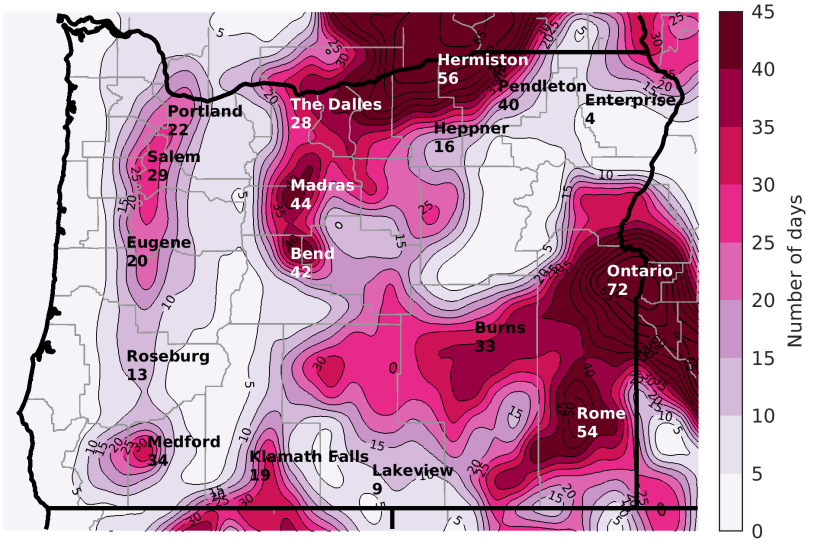

Figure 6. The number of days during 2021 on which the heat index was 90°F (32°C) or above. Heat indexes derived from ERA5 atmospheric reanalysis data.

The annual duration of most Oregonians' exposure to high heat, such as a heat index of 80°F (27°C) or greater (Table 5) or 90°F or greater (Table 6), has increased significantly during the past 40 years. From 1981–2010, the mean annual number of exposure hours at the Willamette Valley stations of Portland, Salem, and Eugene was similar: 320 hours at 80°F or above and 32 hours at 90°F or above. The number of exposure hours at Medford and Pendleton was substantially greater than in the Willamette Valley, whereas the number at Burns was only somewhat greater. Since 2011, the average number of hours of exposure to heat indexes above either 80°F or 90°F has increased throughout Oregon relative to 1981–2010. In Portland, the average number of exposure hours in 2021 and 2022 was more than three times greater than from 2011–2020.

Influence of Climate Change on Extreme Temperatures

Extreme Heat

Daily and annual temperature are highly variable. At a given location on a particular day of the year, the likelihood of a temperature above or below a given value can be estimated with a probability distribution derived from historical temperature observations. Extreme heat and cold can be characterized by their frequency. Moderately extreme events might be expected to recur every 10 years (10 percent probability of occurrence in a given year), whereas more extreme events might be expected to recur every 100 or even 1000 years (1 or 0.1 percent probability of occurrence in a given year, respectively). Models indicate that, as climate changes, the probability of warmer temperatures increases, while the distribution of relatively high and low temperatures remains similar (Figure 7).

Years	Portland	Salem	Eugene	Medford	Pendleton	Burns
1981–1990	301.8	323.5	300.8	701.0	503.8	331.5
1991–2000	315.2	331.0	318.0	715.4	541.2	359.1
2001–2010	324.2	331.4	338.0	758.4	598.0	423.8
2011–2020	331.6	361.5	401.0	842.2	609.1	459.0
2021–2022	537.0	545.5	523.5	954.0	782.5	651.5

Table 5. Average number of hours per year with a heat index 80°F (27°C) or above. Data source: Iowa Environmental Mesonet (mesonet.agron.iastate.edu).

Years	Portland	Salem	Eugene	Medford	Pendleton	Burns
1981–1990	33.4	37.6	27.3	138.9	53.3	19.1
1991–2000	30.8	31.0	30.5	132.1	74.4	20.3
2001–2010	31.3	32.1	30.1	137.3	87.2	21.9
2011–2020	34.6	40.7	41.7	155.8	85.4	24.0
2021–2022	105.0	106.5	97.5	261.5	200.5	117.0

Table 6. Average number of hours per year with a heat index 90°F (32°C) or above. Data source: Iowa Environmental Mesonet (mesonet.agron.iastate.edu).

Climate change will continue to affect extreme heat events in two ways. First, the intensity of extreme heat events will increase further. Consider a scenario in which the mean temperature at a given location increases by 3°F. If the shape of the temperature distribution does not change (Figure 7), then an extreme heat event will be 3°F warmer than in the absence of climate change (e.g., 100°F historically and 103°F in the future). For example, the average daily maximum temperature in Portland is projected to increase by about 3.7°F from 2020 through 2050 (Figure 8). Second, humans'

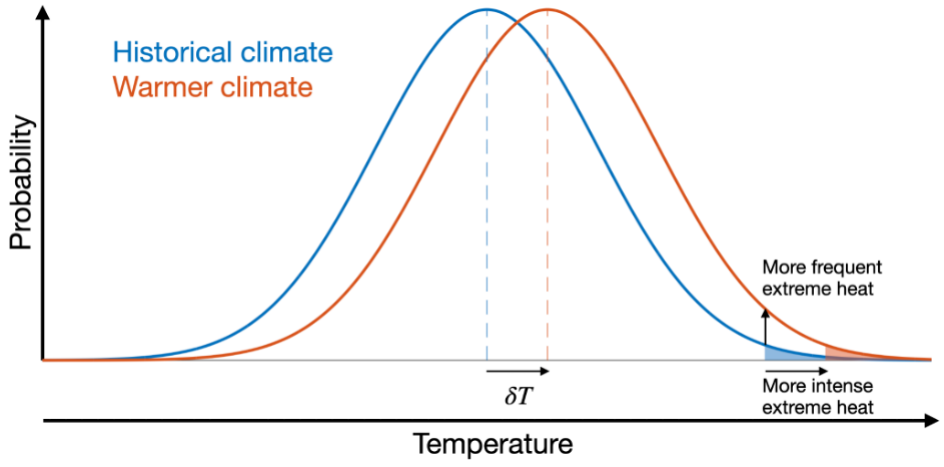

Figure 7. Schematic probability distributions of temperature during a particular season at a given location historically and in the future, warmer climate. Shaded regions at the right tails represent the warmest 0.5 percent of days.

perception of extreme heat will change as the frequency of events currently considered to be extreme increases. For example, temperatures that historically occurred on 0.5 percent of days are projected to become more than twice as common (Figure 7). In Portland during the twentieth century, 100°F temperatures occurred about once every 10 years. By 2025, they are likely to occur about once every 2 years (Figure 8).

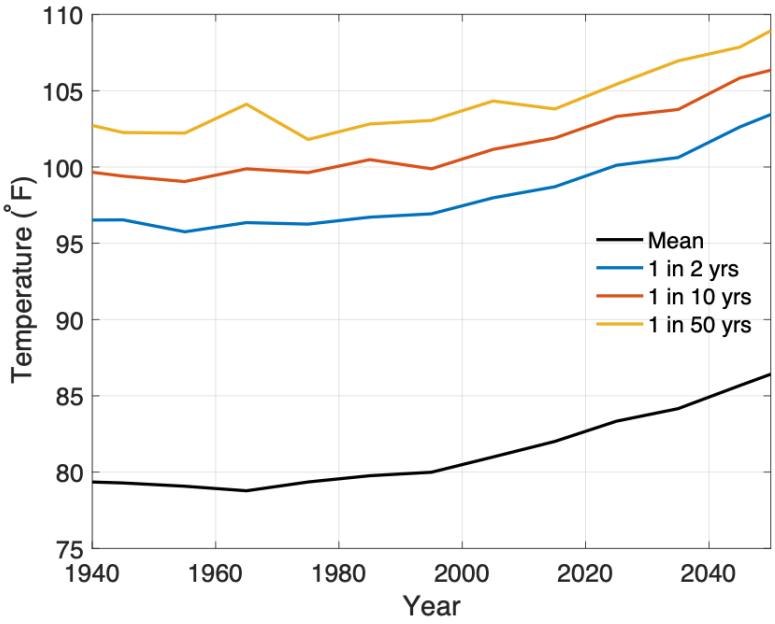

Figure 8. Daily maximum temperature during July and August in Portland, Oregon, as simulated by the CESM1 Large Ensemble (a 35-member set of global climate models) from 1940–2050, assuming a relatively high emissions scenario (RCP 8.5). Black line, mean high temperature; colored lines, temperatures that occur once every 2 (blue), 10 (red), and 50 years (yellow). Values are based on simulated temperatures over 10 years. A bias correction was applied to yield a mean 1990–2020 high temperature that matched observations (81°F).

Although climate models broadly agree that changes in the shape of the temperature distribution will be small relative to changes in mean temperature, some mechanisms might cause a more substantial change in the shape of the temperature distribution. For example, if a decrease in the equator-to-pole temperature gradient, caused in part by the melting of Arctic sea ice, alters the shape and position of the midlatitude jet stream, the temperature distribution could be altered (see *Arctic Amplification*, this volume). Soil-moisture feedbacks also amplify heat waves in some instances (e.g., Zeppetello et al. 2022), such as the European heat wave of 2003 (Miralles et al. 2014). Dry soils can amplify extreme heat events through relative lack of evaporative cooling of the surface. Soil-moisture feedbacks also may have played a role in the June 2021 heat dome (Bartusek et al. 2022), which followed the driest spring in Oregon's recorded history (see *Drought*, this volume). How Arctic amplification and soil moisture feedbacks affect historical and future extreme temperatures is an active area of research.

Extreme Cold

Extreme cold in Oregon is generally associated with cold air outbreaks, in which the jet stream migrates south over the Intermountain West and Arctic air moves into Oregon from the north and east. Because the Arctic is warming more quickly than other regions, the air associated with cold air outbreaks is warming at a greater rate than the global mean temperature, causing a decrease in both the intensity and frequency of extreme cold events (e.g., Screen 2014, Schneider et al. 2015, Holmes et al. 2016, Gross et al. 2020). However, the frequency distribution of Oregon's winter temperatures has a long cold tail that reflects the rare occurrence of extremely cold temperatures (Catalano et al. 2020). This long tail may result in a slow decrease in the frequency of extreme cold (Loikith and Neelin 2019); the rate at which the frequency of extreme heat increases will exceed that at which the frequency of extreme cold decreases. Therefore, although Oregon's coldest temperatures are warming and will continue to warm, rare, extreme cold will still be possible in the coming decades.

Extreme High Heat Index

Climate change is projected to alter both temperature and relative humidity, and thus the heat index. Climate models project little change in relative humidity in Oregon, with a decrease of only a few percent in eastern Oregon during summer by the end of the century. Warming over extensive areas is the primary driver of projected future changes in extreme heat index values in the Pacific Northwest (Schoof et al. 2019).

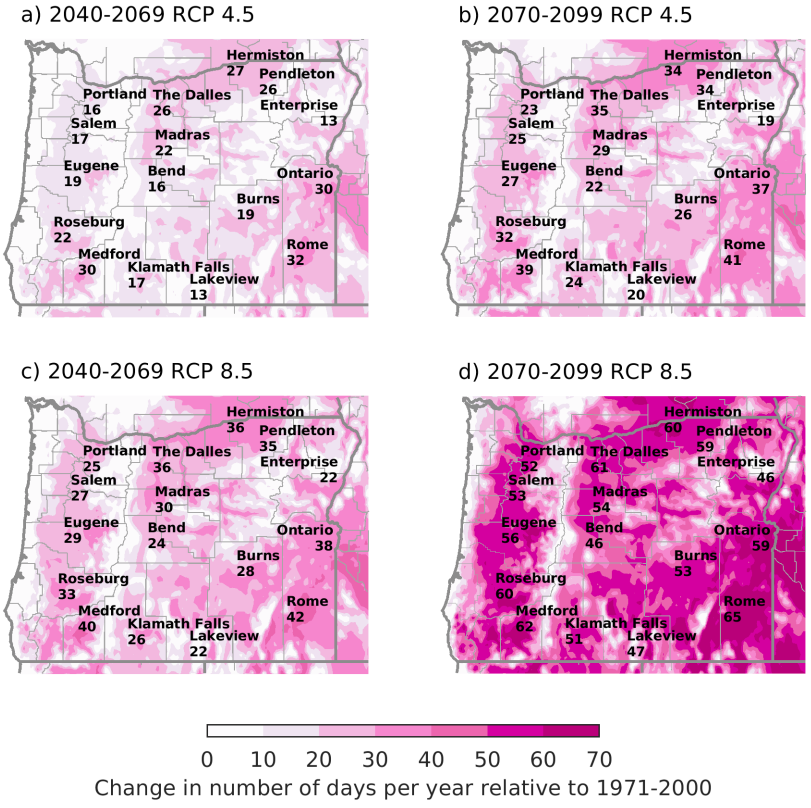

Figure 9. Increase in the projected number of days per year with a heat index of 90°F or above relative to 1971–2000. Values are means of 18 downscaled models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Dahl et al. 2019). Data source: www.climatetoolbox.org.

We consider projected trends in the heat index and temperature separately for two reasons. First, the heat index describes human health impacts better than air temperature and is now the primary metric Oregon uses for regulating heat in work environments. Second, because the heat index has a nonlinear relation to relative humidity, the projected trends in the heat index are not necessarily constrained to follow those in air temperature.

The number of days on which the heat index exceeds 90°F is projected to increase throughout Oregon except at high elevations and on the west side of the Coast Range (Figure 9). Across the majority of Oregon by the mid-twenty-first century, the mean annual number of days with a heat index above 90°F is projected to increase by 15–30 days assuming RCP 4.5 and 25–40 days assuming RCP 8.5 (Figures 8a, c). In the Willamette Valley, the annual number of days with an extreme heat index will be double or triple that from 1991–2020 (Figure 5). The greatest increases in the number of extreme heat index days by the late twenty-first century, 20–40 days assuming RCP 4.5 and 45–65 days assuming RCP 8.5, will occur near Hermiston, Rome, and Ontario. The number of days with an extreme heat index in these areas is already among the highest in Oregon. In some parts of eastern Oregon given the RCP 8.5 scenario, the heat index is projected to exceed 90°F on most summer days. In large part, these exceedances reflect projected increases in warming in eastern Oregon, which are greater than those in western Oregon, throughout the twenty-first century. Projections suggest that if the concentration of greenhouse gases does not decrease, the frequency and magnitude of days with an extreme heat index will increase substantially throughout most of Oregon by the middle and late twenty-first century.

Pacific Northwest Heat Wave of June 2021

During the last week of June, 2021, an exceptional heat wave with no precedent in the modern observational record occurred across Oregon and the Pacific Northwest (Bercos-Hickey et al. 2022, Neal et al. 2022, Thompson et al. 2022, Vescio and Bair 2022, Philip et al. in press). The all-time high temperature records at multiple weather stations were broken by several degrees. Portland's previous all-time record of 107°F (42°C) broke on 26 June (108°F [42°C]), 27 June (112°F [44°C]), and 28 June (116°F [47°C]). Salem's all-time record of 108°F broke on 28 June at 117°F. Previous official all-time record high temperatures of 119°F (48°C) at the Pelton Dam and Moody Farms weather stations were tied (Vescio and Bair 2022). Nights also were extremely warm during this event, although records for warm nights were broken by smaller margins at most major weather stations (for example, 75°F [24°C] at Portland, breaking the previous record of 74°F [23°C]).

This heat wave, which became known as the heat dome, was driven by a remarkable amplification of meteorological features historically associated with heat waves in the region (Bumbaco et al. 2013). The primary driver was a record-breaking ridge of mid-tropospheric high pressure (the heat dome) that peaked just offshore of central British Columbia on 26 and 27 June (Neal et al. 2022). The ridge set all-time records for 500 hPa geopotential height and temperature at the Quillayute upper-air station (Vescio and Bair 2022). Sinking air under this ridge of high pressure warmed thermodynamically and prevented clouds from forming, maximizing solar heating. Additionally, winds were blowing offshore (westward) across the state, preventing any cooling by the Pacific Ocean while increasing the warming in the Willamette Valley as air descended on the west side of the Cascade Range. There is some evidence that widespread dry soils in the western United States may have amplified the already extreme heat wave (Bartusek et al. 2022), consistent with conclusions of other studies indicating that antecedent abnormally dry soils can amplify heat waves through reduction of surface cooling by evapotranspiration (e.g., Zeppetello et al. 2022).

The simplest and most straightforward way to interpret the effect of anthropogenic climate change on the severity of the June 2021 event is to assume that it elevated temperatures by an amount equivalent to the mean increase in temperature since anthropogenic climate change began. A recent study estimated that this heat wave was about two degrees Fahrenheit warmer than it would have been without human influence on the climate (Bercos-Hickey et al. 2022), consistent with the increase in mean temperature. An event of this magnitude is likely to occur once in 1000 to 100,000 years (McKinnon and Simpson 2022, Thompson et al. 2022). A heat dome would have occurred without climate change, but maximum temperatures would not have been as high (McKinnon and Simpson 2022). Thompson et al. (2022) estimated that a heat wave of similar magnitude will recur about once in six years by the end of the twenty-first century if concentrations of greenhouse gases do not decrease. There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest (Loikith et al. 2022). However, the relations between extreme atmospheric circulation patterns and climate change are not yet fully understood.

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Drought

Larry O'Neill and Nick Siler

Over the last three years, one of the most severe droughts in Oregon's recorded history strained the water supply to communities, agriculture, and ecosystems. Water availability is central to the state's economy, contributing significantly to the resilience of agricultural and livestock production, public health, urban environments, energy supply, fisheries, and industry. For example, drought and other climate stressors are affecting Pacific salmon populations that are central to the cultural identities and economies of Indigenous communities (see *Tribal Resilience to Climate Change*, this volume).

Over the last 20 years, the incidence, extent, and severity of drought has increased throughout the western United States, including the Pacific Northwest (e.g., Dalton et al. 2017, Williams et al. 2020, 2022). The likelihood of continued increases in drought severity and duration in the twenty-first century raises questions about how best to prepare for and mitigate the impacts of drought, and to better understand historical and projected future variability of drought. Here, we summarize recent drought variability in Oregon and recent research on drought and water supply relevant to Oregon.

Defining Drought

There are many conceptual and quantitative definitions of drought (Wilhite and Glantz 1985, Rasmussen et al. 1993). The simplest definition of drought is insufficient water to meet demand (Redmond 2002). Drought is generally characterized by a deficit in the supply of water (Swann 2018). However, the precise definition of drought depends on the location and context.

Meteorological drought traditionally has been defined by lack of precipitation, but is better defined as evaporative demand that exceeds precipitation over a prolonged period. Hydrological drought occurs when extended periods of meteorological drought affect surface or subsurface water supply, and is most consequential for society when water supply does not meet human demand. Meteorological and hydrological drought are driven by physical factors and do not describe impacts on humans or ecosystems. Several other types of drought are defined on the basis of their effects on particular components of human and natural systems. For example, agricultural drought occurs when lack of surface or subsurface water supply adversely affects agricultural production. Nevertheless, the effects of meteorological and hydrological drought depend in part on the duration of drought. The Pacific Northwest is prone to seasonal drought due to gaps in wet season precipitation. Flash droughts occasionally occur throughout Oregon (Otkin et al. 2018, Pendergrass et al. 2020). Flash droughts are characterized by rapid-onset periods of elevated surface temperatures, low relative humidities, precipitation deficits, and a rapid decline in soil moisture. These conditions often occur in Oregon during summer heat waves, and the impacts of flash drought can emerge in as little as a week (Mo and Lettenmaier 2015, Rupp et al. 2017).

As the climate warms and the hydrologic cycle changes, the western United States is becoming more arid, and the process and effects of aridification are intensifying (Sherwood and Fu 2014, Cook et al. 2016, Overpeck and Udall 2020, Williams et al. 2022). As distinct from drought, aridification refers to gradual, long-term drying of the climate system. Most of the southwestern United States, extending north to southern and eastern Oregon, is experiencing a megadrought that is estimated to be one of the most severe since at least 800 CE (Williams et al. 2020, 2022). Megadrought generally refers to droughts that persist for longer than a decade, although wet years can occur during a megadrought. Additionally, virtually all of Oregon is in a multiple-year drought, defined as drought

that persists for more than one water year. Impacts on human and natural systems can become more severe in each consecutive year of drought as groundwater, soils, and surface-water bodies continually dry without normal recharge.

Oregon and much of the western United States depend on mountain snowpack. Snow acts as a large, natural reservoir of water that accumulates during winter and is released slowly during spring and summer. The concept of snow drought is particularly relevant in snowmelt-dominated watersheds. Snow droughts are typically defined as a deficit in snow water equivalent (SWE; the amount of water contained in the snowpack) on 1 April (Harpold et al. 2017, Hatchett and McEvoy 2018). Years with poor snowpack often presage hydrological drought conditions during the ensuing spring and summer in snowmelt-dominated watersheds (Sproles et al. 2017) as impacts from lack of water at high elevations cascade through the watershed. In recent years, two types of snow drought occurred in Oregon. Warm snow droughts, such as the drought that occurred in 2015 (Cooper et al. 2016, Mote et al. 2018), are primarily the result of above-average winter temperatures. Dry snow droughts, such as the 2020–2022 drought in the central and south Cascade Range in Oregon, are mainly the result of below-average winter precipitation. Snow droughts may be both warm and dry. For example, during the 2022 water year (defined as October 2021–September 2022), below-average high-elevation precipitation in Oregon coincided with well-above-average temperatures at elevations above 3000 ft (914 m). On 28 March 2022, the average SWE value for all of Oregon's SNOTEL stations was 37 percent below the median.

Historical Trends in Drought Severity and Extent

In 17 of the last 23 water years, Oregon's precipitation was below average (Figure 1). In terms of precipitation, water years 2001 and 2020 ranked as the third and fifth driest water years in Oregon

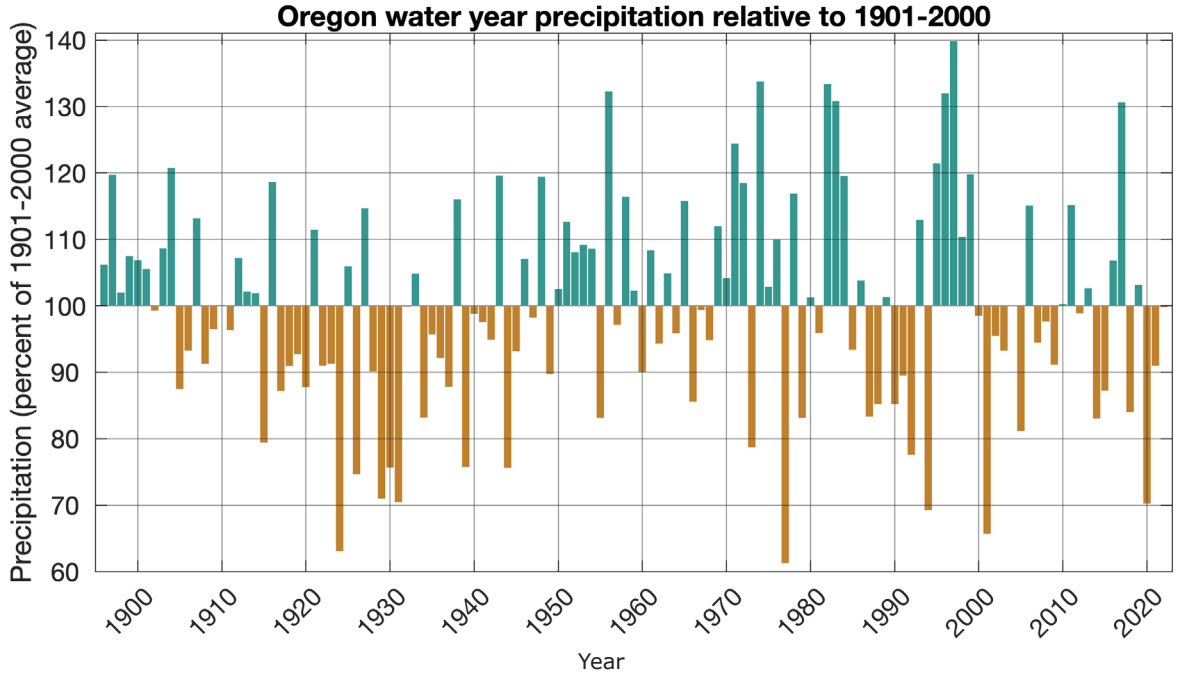

Figure 1. Time series of total water year precipitation averaged across Oregon. Data from the PRISM Climate Group and accessed via the West Wide Drought Tracker, wrcc.dri.edu/wwdt/time, with the following selections: Oregon, Precipitation, 1895–2022, September, 12-month; accessed 5 December 2022.

since 1895. The average temperature in Oregon also was warmer than normal in 18 of the last 23 water years (Figure 2), which contributed to increases in evapotranspiration and drought frequency.

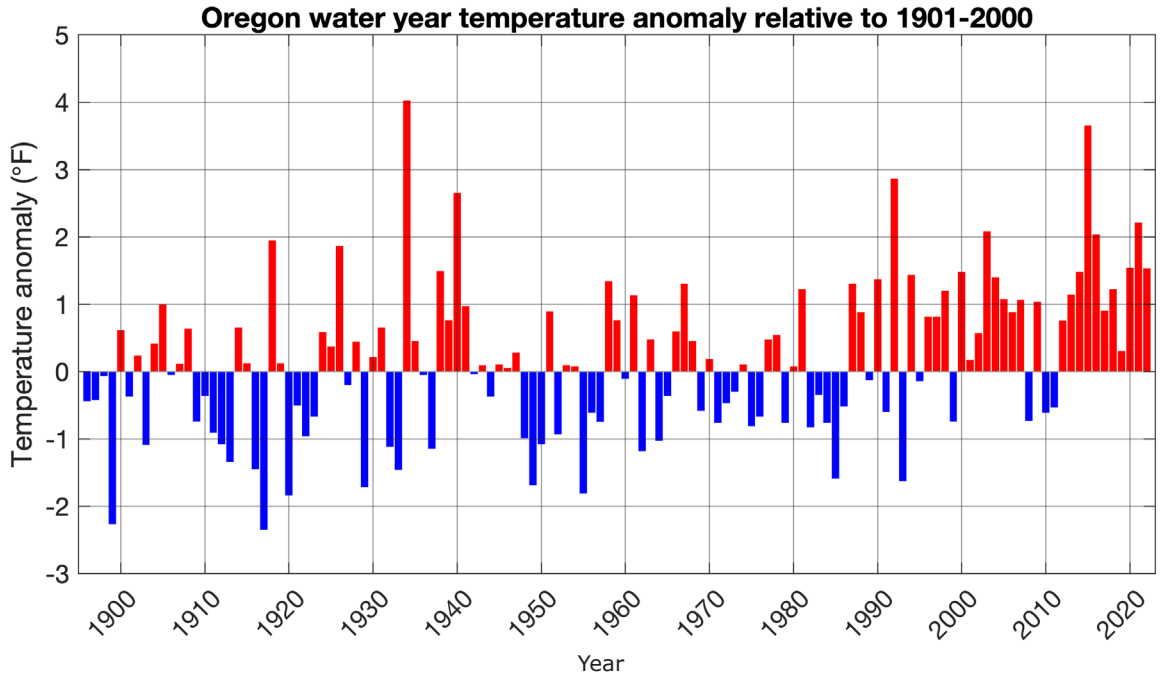

Figure 2. Time series of water year average temperature in Oregon. Data from the PRISM Climate Group accessed via the West Wide Drought Tracker, wrcc.dri.edu/wwdt/time, with the following selections: Oregon, Temperature, 1895–2022, September, 12-month; accessed 5 December 2022.

The dimensionless Standardized Precipitation-Evapotranspiration Index (SPEI) is a primary quantitative metric for assessing the existence and severity of meteorological and hydrological drought, especially in the western United States (Vicente-Serrano et al. 2010). The SPEI compares the net water balance between precipitation and potential evapotranspiration (evapotranspiration from a large area with uniform vegetation and unlimited soil water) between a recent period of time and a historical period (Vicente-Serrano et al. 2010). The SPEI allows for evaluation of drought severity in different locations and time periods, identification of different drought types (Ahmadalipour et al. 2017), and consideration of the role of temperature-driven evapotranspiration in drought. The 12-month SPEI is a reliable predictor of annual streamflow in the Pacific Northwest (Abatzoglou et al. 2014a, Peña-Gallardo et al. 2019) and water levels in lakes and reservoirs (McEvoy et al. 2012). Accordingly, the SPEI at extents between 3 and 24 months is a key indicator of drought severity and extent in the U.S. Drought Monitor for Oregon. The U.S. Drought Monitor provides a consistent overview of drought conditions nationwide. It combines multiple indicators of dryness, including precipitation, snowpack, streamflow, soil moisture, groundwater, and evapotranspiration, at multiple temporal extents, into a single drought severity classification (Svoboda et al. 2002).

During water year 2020, the 12-month SPEI in Oregon was at its lowest value since 1896 (Figure 3). By this measure, the drought was the most severe in Oregon's recorded history, exceeding 1924, 1931, 1977, and 1994 (Xiao et al. 2016). The 2020 drought was driven by a combination of low precipitation and high evapotranspiration, which in turn reflected well above normal temperatures (Bumbaco et al. 2021).

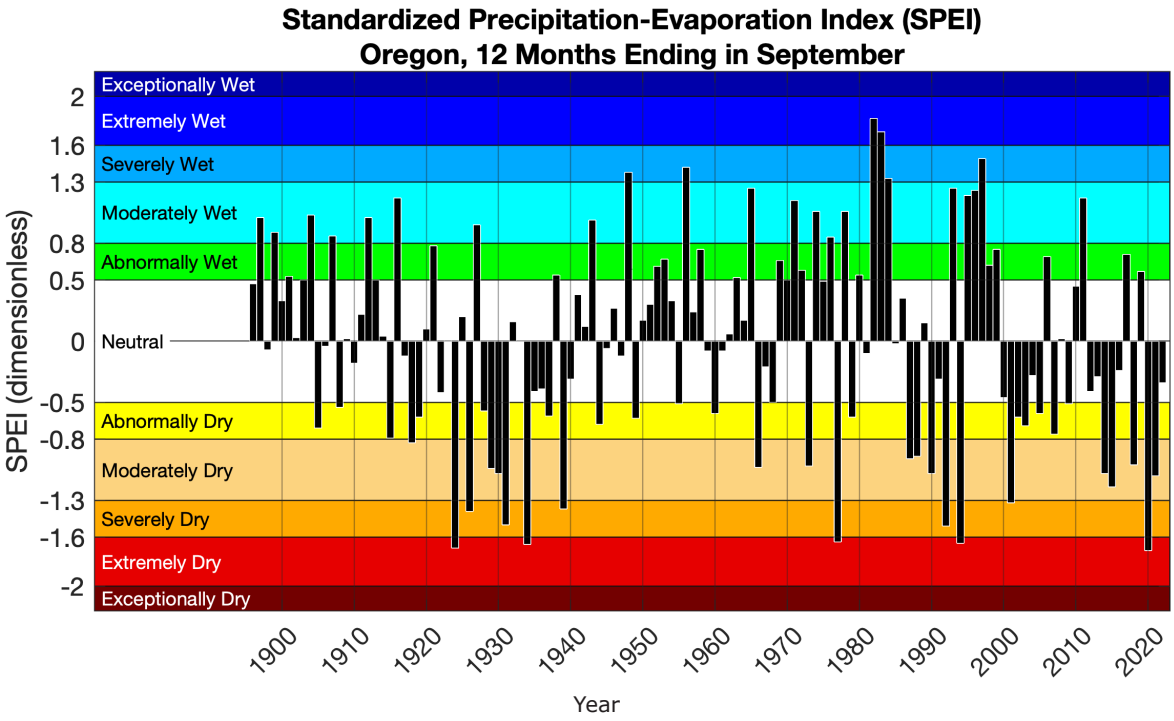

Figure 3. Time series of the Standardized Precipitation-Evapotranspiration Index (SPEI) for each water year since 1896 for the state of Oregon. Data from the PRISM Climate Group accessed via the West Wide Drought Tracker, wrcc.dri.edu/wwdt/time, with the following selections: Oregon, SPEI, 1895–2022, September, 12-month; accessed 5 December 2022.

Yearly estimates of soil moisture from tree rings suggested that the years 2000–2021 were the driest in the southwestern United States since at least 800 CE (Williams et al. 2022). In Oregon, this 22-year period was among the five driest such periods since 800 CE. These years were characterized by low snowpack, decreased summer streamflow, low precipitation during all seasons, and steadily rising evaporative demand due to climate change-induced aridification.

Persistent and severe droughts have occurred in Oregon since 2000. These droughts were caused by different conditions, such as low winter precipitation and snowpack (2001), low summer precipitation and high winter temperature (2003), and low snowpack and low winter precipitation (2005) (Bumbaco and Mote 2010). Low precipitation contributed to each drought, but temperature and snowpack also affected drought severity and impacts, including the propagation of meteorological drought to hydrological and agricultural drought (Bumbaco and Mote 2010). Multiple studies have related cooler sea surface temperatures in the eastern Pacific Ocean, which typically are associated with La Niña, and the 1998–2004 drought and other historical droughts in the western United States (Hoerling and Kumar 2003, Cook et al. 2007, Seager 2007, Wise 2016). An estimated 19 percent of the soil moisture deficits in the West from 2000–2021 are attributable to anthropogenic climate change (Williams et al. 2022).

Anticipated Impacts of Climate Change on Drought

Most global climate models project that annual mean precipitation will increase in Oregon by five to ten percent by 2100 (e.g., Almazroui et al. 2021). Precipitation is projected to increase during winter but decrease during summer (Abatzoglou et al. 2014b, Rupp et al. 2017), which implies an increase in the number of consecutive days without rain during the dry season. Some studies suggested that

precipitation events and dry periods will become more intense in the coming decades (Pendergrass et al. 2017, Rupp et al. 2022). However, changes in total annual precipitation will continue to be driven primarily by annual variation rather than long-term trends (Rupp et al. 2017).

Evaporation is generally expected to increase in Oregon as temperatures increase (Abatzoglou and Rupp 2017). Warm air holds more moisture than cool air, so projected increases in total evaporation are driven by projected increases in vapor pressure deficit. Even if the net water balance (precipitation minus evaporation) increases on average, the likelihood of drought, particularly during summer, increases as precipitation becomes more intense and seasonal. Under the moderate (RCP 4.5) and high (RCP 8.5) emissions scenarios, the severity and duration of droughts, as characterized by the three-month SPEI, were projected to increase across most of Oregon (Gu et al. 2020). Seasonal droughts were projected to be 11–33 percent longer and at least 40 percent more severe by the end of the century (Gu et al. 2020).

Across Oregon, snow water equivalent declines of approximately 25 percent are projected by 2050 relative to 1950–2000 (Siirila-Woodburn et al. 2021). These losses are similar to declines that already occurred in the late twentieth and early twenty-first century. As climate change reduces mountain snowpack in the western United States (Livneh and Badger 2020, Siirila-Woodburn et al. 2021), snow droughts will increase the likelihood of hydrological or agricultural drought during the following spring and summer (Koster et al. 2010, Wood et al. 2016, Harpold et al. 2017), and seasonal drought will become less predictable (Marshall et al. 2019, Livneh and Badger 2020).

It is still unknown whether conditions similar to the 2015 or 2022 snow droughts may become common in Oregon by the mid-twenty-first century (Cooper et al. 2016, Dalton et al. 2017). An analysis of historical climate data suggested that for every 1°C of warming, peak SWE decreases by up to 30 percent (Cooper et al. 2016). Effects of anthropogenic climate change on spring snowpack trends since 1980 may have been mitigated by natural variability produced by changes in atmospheric circulation over large areas that were driven by sea surface temperatures in the North Pacific Ocean (Siler et al. 2019). Declines in western United States snowpack may accelerate once the cycle of natural variability shifts (Siler et al. 2019). Projections assuming RCP 8.5 suggest that winter snowpack in the Pacific Northwest will decrease by more than 60 percent by 2050 (Fyfe et al. 2017, Shrestha et al. 2021). The average number of water years that are encompassed by a snow drought of two or more years also is projected to increase from 7 percent (1970–1999) to 42 percent by 2050–2070 (Marshall et al. 2019).

The social and economic effects of snow drought may be considerable in basins that rely more heavily on irrigated water derived from snowmelt runoff. For example, snowmelt runoff accounts for about 25 percent of total surface water allocated to irrigation in the Columbia River basin (Qin et al. 2020). The Willamette River basin is also vulnerable to projected decreases in Cascade Range snowpack and snowmelt runoff, with increased incidence of short-term agricultural drought during summer (Jung and Chang 2012). Short-term drought during the growing season may have major effects on agricultural productivity if water for irrigation becomes limited and soil moisture is not recharged. Watersheds in the Pacific Northwest that receive both rain and snow, and in which snowmelt runoff makes a substantial contribution to spring and summer streamflow, are the most sensitive to projected winter warming (Vano et al. 2015). The frequency of hydrological drought is projected to increase in such watersheds.

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Changes in the Water Cycle and the Contributions of Community Science

Contemporary discussion of the hazards that changes in the water cycle pose to Oregon often focus on drought and changes in the proportion of precipitation falling as rain rather than snow. As Fountain explains in this section, the amount of water stored in Oregon's glaciers and perennial snowfields also is changing as glaciers disappear and retreat in the state's major mountain ranges.

Weather and climate mapping systems long have relied on data from networks of observation stations, such as those operated by the National Oceanic and Atmospheric Administration's National Weather Service and the U.S. Department of Agriculture's Natural Resources Conservation Service. Increasingly, however, professional meteorologists and climate scientists are capitalizing on the expertise and generosity of members of the public, or community scientists, who measure precipitation in areas without formal observation stations. For example, as described in this section by Daly and Newman, the PRISM climate mapping system is now regularly incorporating information from thousands of community observers. These data contribute to development of 30-year climate normals, updates to Plant Hardiness Zone maps, and numerous other resources that support diverse economic, recreational, and scientific sectors. The most comprehensive community science network contributing to PRISM—with more than 25,000 active volunteers across the United States and Canada—is the Community Collaborative Rain, Hail, and Snow network (CoCoRaHS).

Two additional community science programs highlighted in this section, Community Snow Observations (CSO) and Mountain Rain or Snow, exemplify how community scientists have dramatically expanded the geographic scope of precipitation sampling and enhanced the reliability of hydrologic models. For example, Hill and the CSO team illustrate how community data have improved models of snow depth. Similarly, Collins and collaborators at Mountain Rain or Snow demonstrate the advances in understanding when precipitation falls as rain, snow, or mixed, and the probability of snowfall as a function of air temperature, that have been facilitated by community observations. Moreover, community participation increases the accessibility of science and scientific literacy. We hope that this section will pique some readers' interest in becoming new members of one or more community observation programs.

Glacier Change in Oregon

Andrew Fountain

Glaciers advance during cold climatic periods and retreat during warm periods. Thus, glaciers provide tangible evidence of climate change. Changes in winter snowfall and air temperature (summer and winter) are the most important factors affecting changes in the extent of glaciers (Cuffey and Paterson 2010, Fountain et al. 2022).

Glaciers are relevant to natural and human systems because they act as frozen reservoirs that release water when it is needed most—during the hot, dry late summer when seasonal snow has all but disappeared (Fountain and Tangborn 1985, Moore et al. 2009, Carey et al. 2017). Glacial melt protects high alpine ecosystems from the effects of drought, and maintains a flow of cool water. Shrinking glaciers change the hydrology and ecology of downstream systems, and reduces benefits to cold-adapted aquatic species, including insects (e.g., species of *Dimesa*) and bull trout (*Salvelinus confluentus*) (Milner et al. 2017, Lencioni 2018). Glacial melt also supports agriculture. For example, apple and pear orchards on the north slopes of Mount Hood are watered by the Middle Fork of the Hood River, which drains the Coe and Eliot glaciers. Modeling suggests that September flow along the Middle Fork will decrease by almost 70 percent by 2100 due to the loss of glacier area (Nolin et al. 2010, Frans et al. 2018).

Glaciers and perennial snowfields are common in the Cascade Range and the Wallowa Mountains (Figure 1). Glaciers are defined as perennial snow and ice that moves, whereas a perennial snowfield does not move. The first complete inventory of glaciers and perennial snowfields in Oregon was completed by the U.S. Geological Survey (USGS) with aerial photography (Fountain et al. 2007, 2017) as part of an effort to map the topography and geographic features of the contiguous United States in detail (Usery et al. 2009). Aerial images of Mount Jefferson, the rest of the Cascade Range, and the Wallowa Mountains were captured in 1949, 1956–1957, and 1981, respectively. The resulting maps identified 301 glaciers and perennial snowfields that collectively covered 41.6 km^2 (16 mi^2). The features initially were not classified by the USGS, but were classified later on the basis of their topography, yielding 48 glaciers (31.7 km^2 [12.2 mi^2]) and 253 snowfields (9.9 km^2 [3.8 mi^2]) (Fountain et al. 2017).

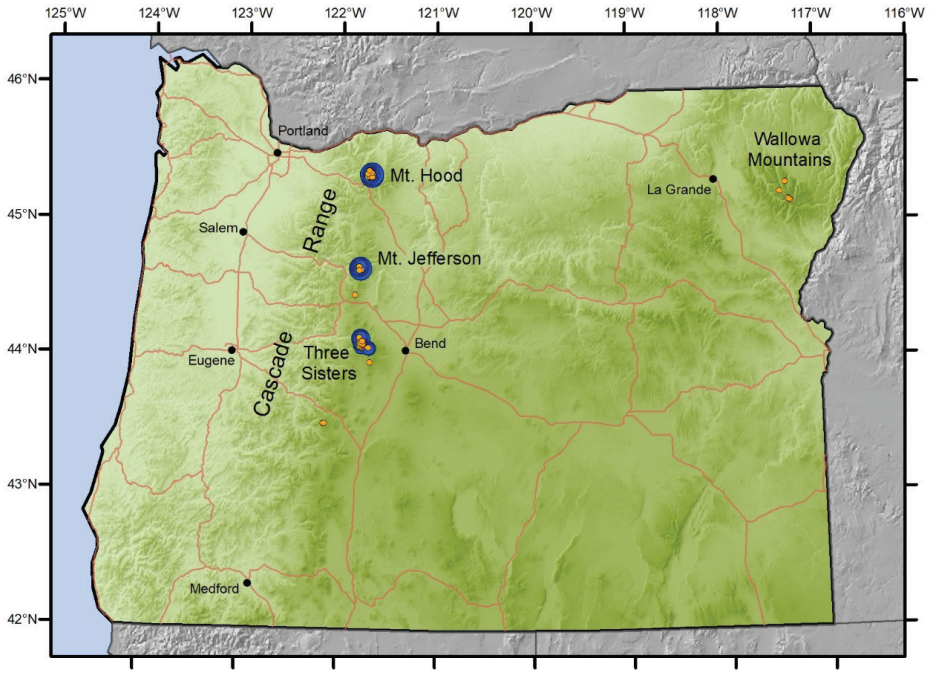

Figure 1. Locations of contemporary glaciers (blue dots) and perennial snowfields (yellow dots) in Oregon.

We compiled an updated inventory of glaciers and perennial snowfields across the western continental United States from high-resolution (~1 m) color aerial imagery acquired over the period 2014–2018. Not all imagery was used because of local variation in seasonal snow-cover; instead, we used the single best image from this period. The inventory identified all glaciers and perennial snowfields that were larger than 0.01 km^2, the international standard for such inventories (Paul et al. 2010). Glaciers were identified by the presence of ice and crevasses; perennial snowfields do not have crevasses. We examined the past 20 years of aerial and satellite imagery in Google Earth to ensure that the absence of crevasses was not due to temporary snow cover. The updated inventory includes 39 glaciers (11.8 km^2 [4.6 mi^2]) and 69 snowfields (2.3 km^2 [0.9 mi^2]).

Since the initial mapping of glaciers by the USGS, 20 glaciers have disappeared, meaning they were smaller than our minimum threshold of 0.01 km^2, showed no movement, or no snow or ice was present. In the Cascade Range, those glaciers included Thayer on North Sister; Irving, Skinner, Carver, and Clark on South Sister; Palmer on Mount Hood; and Lathrop on Mount Thielsen. Benson Glacier, the last glacier in the Wallowa Mountains, also was lost. Lathrop Glacier is a particular case in that it always has been smaller than the minimum area threshold, but we include it here for completeness. The differences between the inventories, in terms of both number and area of glaciers and perennial snowfields, are probably somewhat inflated because the USGS imagery was taken during a single summer and the resulting maps may have overestimated the area of some glaciers and snowfields due to remnant seasonal snow.

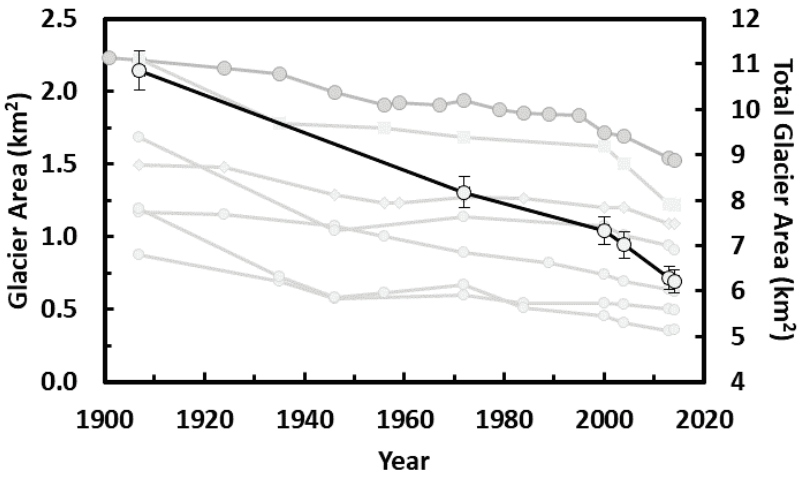

Figure 2. Total area of glaciers on Mount Hood (black line) and the area of the seven major glaciers on the mountain. The photographic record of Eliot Glacier (highest line) since 1990 is the most extensive. The six points on the total-area line indicate the years for which the area of all seven glaciers can be estimated from photographs.

An analysis of glaciers on Mount Hood and the Three Sisters paints a more accurate picture of glacier change in Oregon. Mount Hood (3426 m [11,240 ft]), a volcano east of Portland, hosts seven major glaciers and has the most extensive glacier cover in the state. We used historic photographs and more recent aerial imagery to compile a history of change in glacier area on Mount Hood (Jackson and Fountain 2007). The glaciers have retreated since 1907. Most stabilized or advanced slightly in the 1960s and 1970s. Then retreat continued, and accelerated in the 1990s (Figure 2). In 1907, the combined area was 10.85 ± 0.43 km^2 (4.19 ± 0.17 mi^2), and the sizes of individual glaciers varied from 2.22 km^2 (0.86 mi^2) (Eliot and Newton Clark glaciers) to 0.87 km^2 (0.34 mi^2) (Reid Glacier). By 2014, the total area shrank to 6.21 ± 0.26 km^2 (2.40 ± 0.10 mi^2), with individual sizes from 1.52 km^2 (0.57 mi^2) (Eliot Glacier) to 0.36 km^2 (0.14 mi^2) (White River). The pattern of retreat of Eliot Glacier, the largest and most extensively studied glacier on the mountain (Figure 3), is characteristic of glaciers in the Northwest.

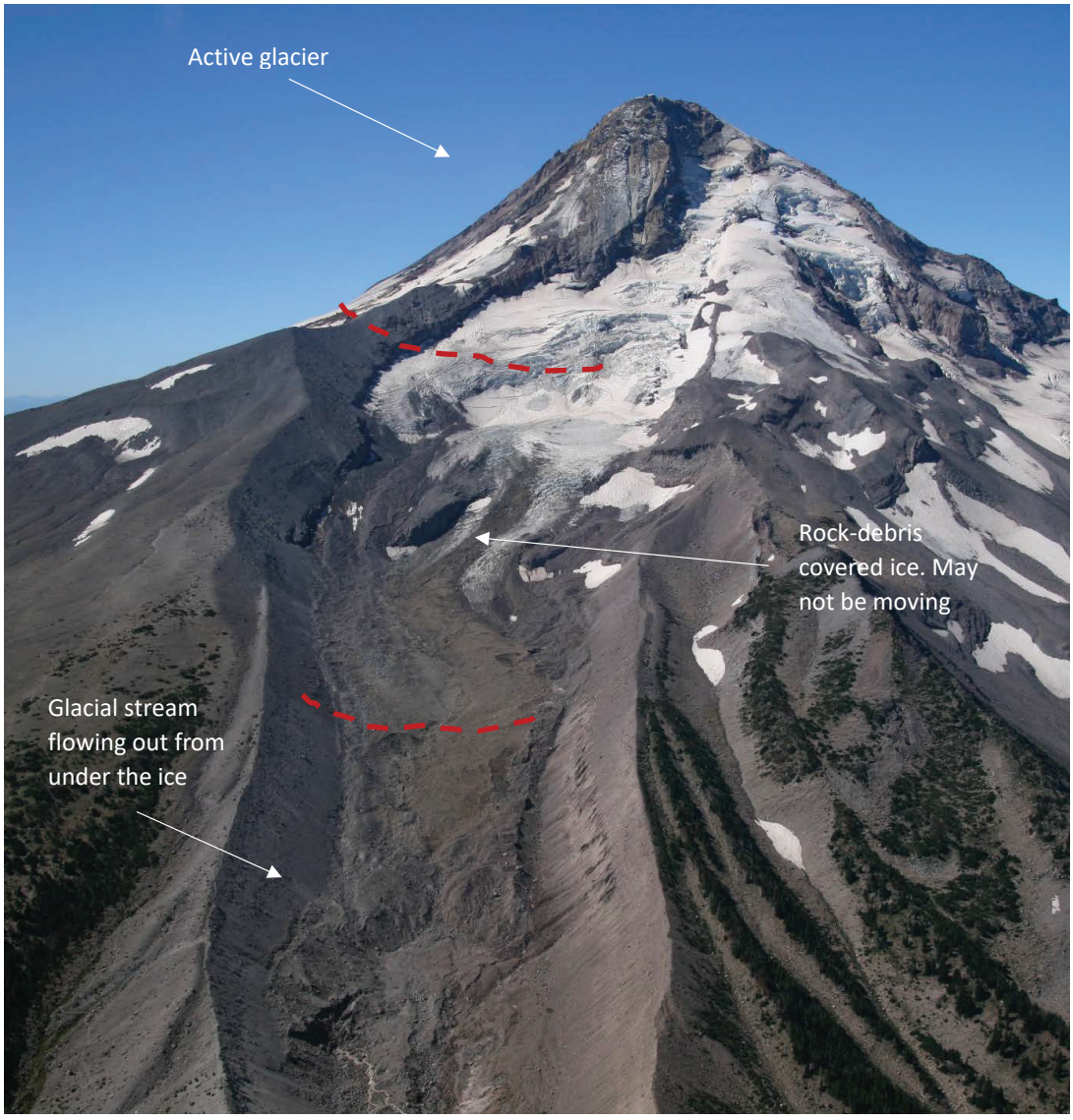

Figure 3. Eliot Glacier on Mt. Hood on 24 August 2007. Note the rock debris-covered ice lower on the glacier. This ice may not be moving and would not be considered part of the glacier. The upper dashed line is the current (2022) extent of the active ice-exposed glacier. The lower dashed line is the current extent of the buried ice. Photograph by John Scurlock.

The other most glacier-covered region in Oregon is the Three Sisters. In 1900, the total area of the 15 glaciers on the Three Sisters, estimated on the basis of geologic evidence left by the glacial moraines, was about 11.7 km^2. By 2018, the total glacier area was 3.0 km^2 (1.2 mi^2), excluding the four glaciers that had become perennial snowfields (Carver, Clark, Irving, and Skinner). Similar to the glaciers on Mount Hood, the glaciers retreated during the early half of the twentieth century, advanced in the late 1950s and 1960s, then resumed retreating, with accelerated retreat starting around 2000 (Figures 4, 5).

The overall change in the glaciers reflects the climate of the Northwest. A global cool period, the Little Ice Age, ended in the mid-late 1800s, and the warmer climate led the glaciers to recede through the early 1900s (O'Connor et al. 2001, Koch et al. 2009, Miller et al. 2012). A cool period during the 1950s and 1960s caused the glaciers to either stop receding or advance somewhat (Hubley

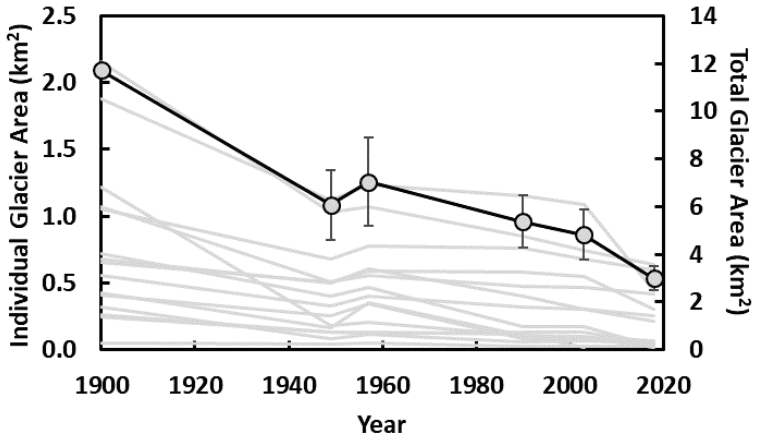

Figure 4. Change in the area of glaciers on the Three Sisters. The solid black line indicates the total glacier area and the light grey lines the area of individual glaciers.

Figure 5. Paired images of the Collier Glacier on North Sister. Top: Collier Glacier, 2020. Bottom: 2020 image with an inset of the glacier in 1934. 1934 photograph by Ruth Hopson Keen; 2020 image by Andrew Fountain.

1956, Lillquist and Walker 2006). Since then, retreat of the glaciers has continued, and accelerated in the 1990s (Hodge et al. 1998, Lillquist and Walker 2006, Jackson and Fountain 2007). Some of this retreat is due to anthropogenic climate warming (Barnett et al. 2008, Fountain et al. 2022).

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The PRISM Climate Mapping System and CoCoRaHS Community Observer Network

Christopher Daly and Noah Newman

Spatially explicit data on weather and climate, usually in the form of continuous grids of pixels, often are key inputs to decision-support systems and tools that require environmental data. These grids typically describe conditions at monthly or daily resolution, and are especially useful because their wall-to-wall estimates of weather and climate encompass areas where weather stations do not currently exist. The most widely used spatial climate data in the United States are those developed by Oregon State University's PRISM Climate Group, which is named for the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system. The PRISM Climate Group is part of the Northwest Alliance for Computational Science and Engineering (NACSE) within the university's College of Engineering.

The PRISM approach to computerized climate mapping was first developed by Christopher Daly in 1991. The PRISM algorithm was written to mimic the decisions an expert climatologist makes while mapping long-term average temperature and precipitation (Daly et al. 1994). In computer science, this kind of model is called an "expert system" (Daly et al. 2002). Since its inception, PRISM has undergone nearly constant development, and has been operationalized to produce monthly and daily time series of an expanding list of meteorological variables, including precipitation, temperature, dew point, vapor pressure deficit, and solar radiation (Daly et al. 2021, Rupp et al. 2022). PRISM simulates how weather and climate vary spatially as a function of the physiography of Earth's surface, such as elevation and coastlines, and uses novel topographic indices to identify areas that are subject to temperature inversions and rain shadows (Daly et al. 2008). Each PRISM grid covers the conterminous United States with millions of grid cells, each

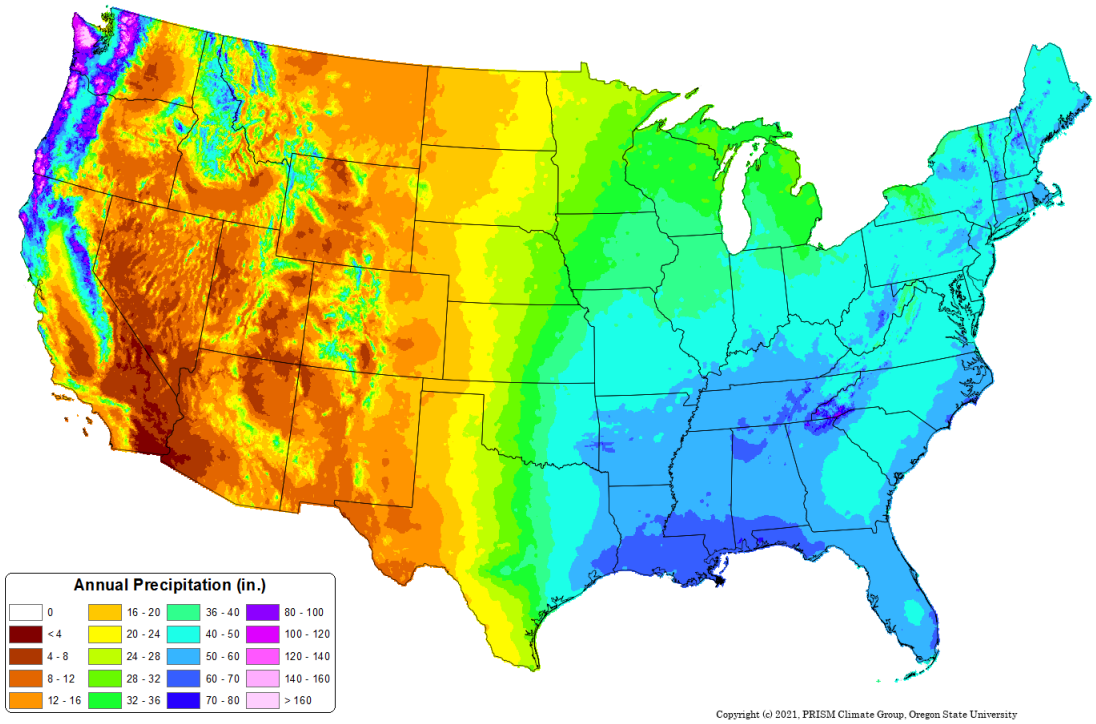

Figure 1. PRISM 1991–2020 normal annual precipitation for the conterminous United States.

approximately 800 x 800 m (1/2 x 1/2 mile), and also at 4 x 4 km (2.5 x 2.5 mile) resolution (prism.oregonstate.edu; Figures 1 and 2).

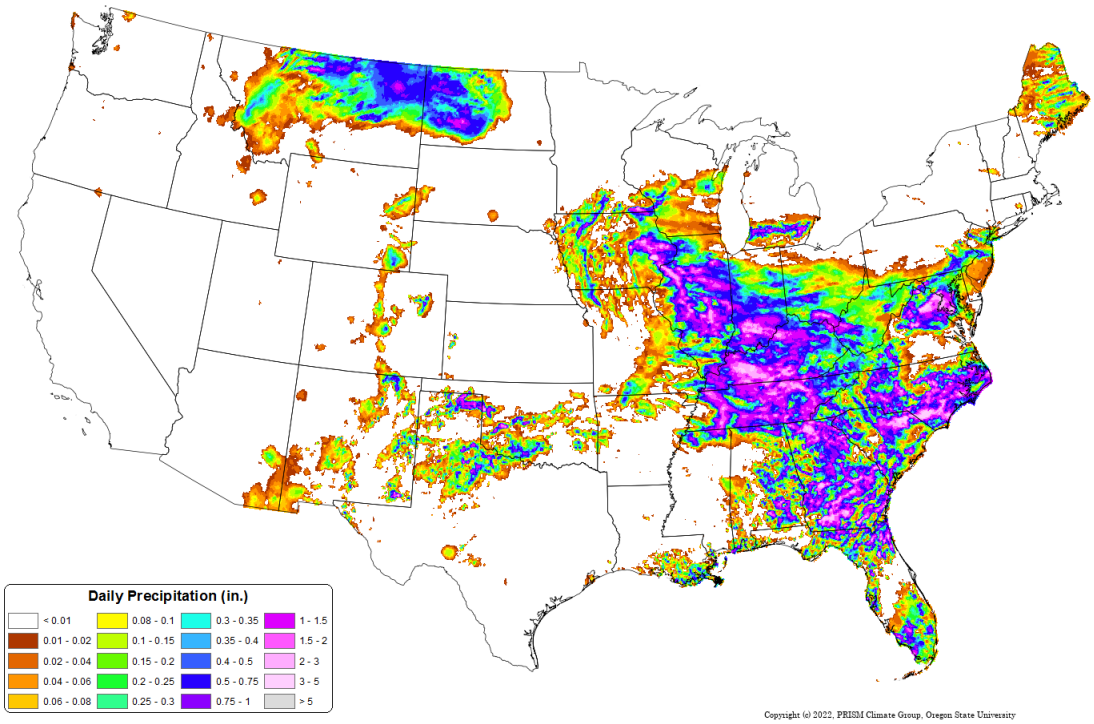

Figure 2. PRISM total daily precipitation on 9 July, 2022, for the conterminous United States.

Users download approximately one million PRISM spatial datasets each month from PRISM's public website (prism.oregonstate.edu). Nearly all U.S. government agencies use PRISM data. Furthermore, the private sector applies PRISM data to agriculture, hydrology, engineering, ecology, economics, and retail. The PRISM Climate Group developed the 2012 U.S. Department of Agriculture Plant Hardiness Zone map, which has been accessed millions of times by gardeners, farmers, horticulturists, and others (Daly et al. 2012). Moreover, the U.S. National Weather Service (NWS) and The Weather Channel have used PRISM data to guide the spatial patterns of their weather forecasts. Peer-reviewed scientific papers on PRISM have been cited in over 14,000 publications.

Contributions of the CoCoRaHS Community Network

Development of accurate, detailed, spatially explicit weather and climate data relies on a large quantity of high-quality station data. Each day, the PRISM Climate Group compiles data from more than 20,000 precipitation and 10,000 temperature stations that are members of federal, state, or regional networks. Because precipitation is sporadic and highly variable, particularly dense data are necessary to accurately quantify precipitation across large or topographically complex areas. Nearly 90 percent of the precipitation stations that contribute to the PRISM datasets are operated by community scientists, and are essential for filling gaps between automated weather stations. The largest of these community science networks is the Community Collaborative Rain, Hail and Snow network (CoCoRaHS; www.cocorahs.org), operated by the Colorado Climate Center.

CoCoRaHS's 25,000 active volunteers in all states, territories, and provinces in the United States and Canada measure and report precipitation from their selected locations, primarily residences but

increasingly schools, libraries, public parks, and workplaces. The network documents approximately 14,000 observations of precipitation or its absence each day, including more than 400 in Oregon (Figure 3). CoCoRaHS has grown from a local community project in Colorado, which began after a flash flood in 1997, to the largest source of daily, manual precipitation measurements in the United States (Reges 2016). With the goal of creating a dense network of high-quality precipitation data, CoCoRaHS volunteers have now submitted over 55 million daily reports that are used by the National Oceanic Atmospheric Administration (NOAA) and its many entities (NOAA 2021). For example, NWS incorporates CoCoRaHS data into daily operational products, and the National

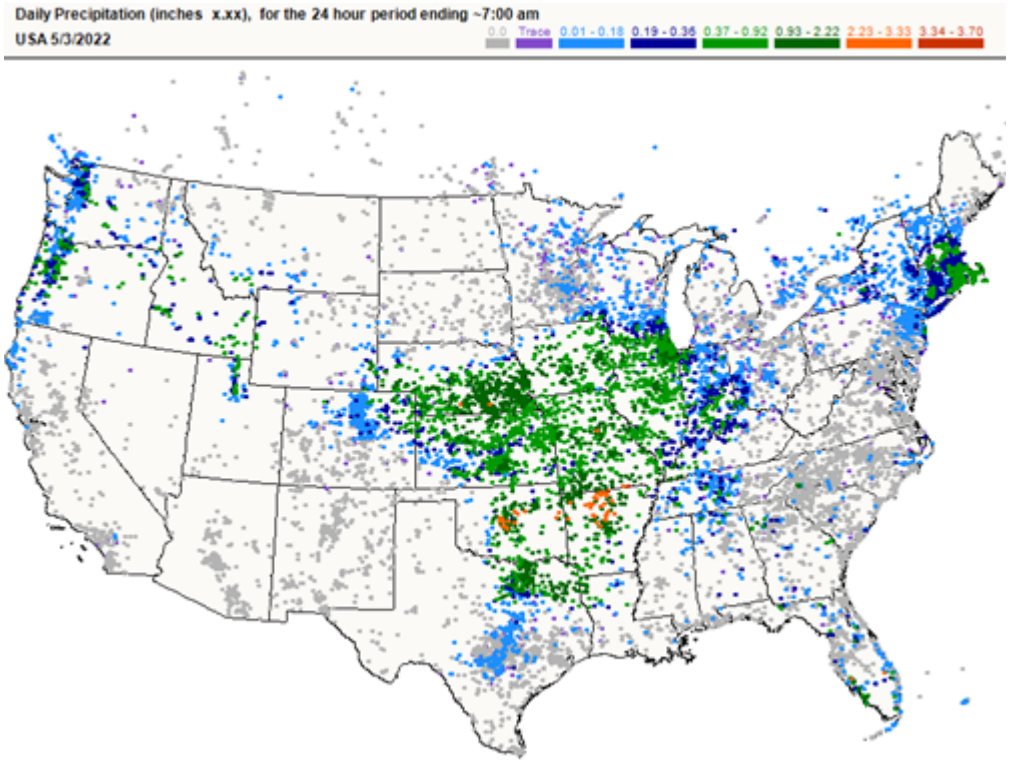

Figure 3. Data from CoCoRaHS observers documented the 24-hour precipitation totals ending at 7:00 a.m. local time on 3 May, 2022.

Centers for Environmental Information (NCEI) uses CoCoRaHS data in its climate research. CoCoRaHS also provides tools that enable volunteers to perform their own analyses, such as comparing monthly precipitation totals to 30-year PRISM averages for their locations (Figure 4).

CoCoRaHS observers measure not only rain but snowfall, snow depth, snow water equivalent (SWE; the amount of water in the snowpack), and hail size and amount. These measurements of SWE account for more than half of the ground-based observations used by NWS for its hydrologic models and predictions. Additionally, many observers submit notes with their observations, which can help to confirm an unusual rainfall or snowfall report during the quality assurance process. If a question about an observation remains, the CoCoRaHS quality control meteorologist is able to contact the observer directly to confirm the observation. This level of validation rarely is possible when data are gathered by automated weather stations rather than stations staffed by people.

CoCoRaHS requires volunteers to use a particular manual gauge that meets NWS standards and conducts extensive quality control and quality assurance processes, both automated and manual.

The CoCoRaHS leadership provides numerous engaging slideshows and videos that train observers on best practices, which helps to ensure that the measurements and reporting are consistent. Furthermore, NCEI performs their own quality assurance processes before data are disseminated to the NWS.

In 2021, NCEI completed their scheduled, decadal update of 30-year climate normals to cover the years 1991–2020. Although no CoCoRaHS station has been operating for 30 years yet, NCEI uses alternative methods to calculate normals on the basis of shorter periods of data. For the first time, data from CoCoRaHS stations were included in the updated normals; NCEI classified 4688 stations as pseudo-normal and 760 as provisional normal. To qualify for pseudo-normal status, data for every day in a given month in at least two years must be available. To qualify for provisional normal status, data for every day in a given month in at least ten years must be available. For data users, the updated normals are analogous to U.S. Census data. In the development of PRISM gridded normals for 1991–2020 (e.g., Figure 5), an activity separate from that of NCEI, 5419 CoCoRaHS stations qualified for inclusion for at least one month of the year. For a given month to be included in the PRISM normals, at least ten years or five years of complete data (for stations in the eastern and western United States, respectively) must be available. Inclusion of the CoCoRaHS data in the NCEI station normals and the PRISM gridded normals allows users to compare present-day conditions to long-term averages more thoroughly (Figure 4).

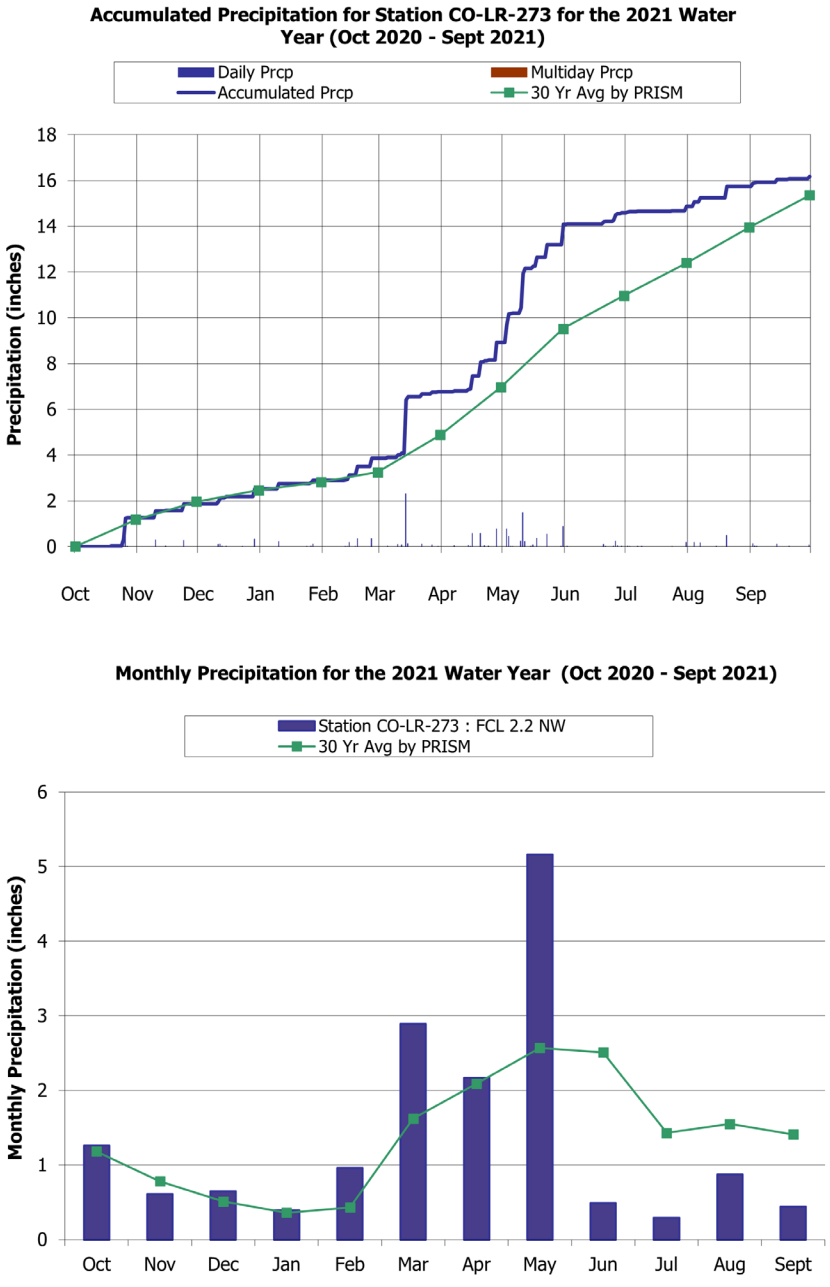

Figure 4. CoCoRaHS observers have immediate access to data analysis tools that are also available publicly, such as tools for summarizing total monthly precipitation (top) and long-term modeled average precipitation (bottom) for a given location.

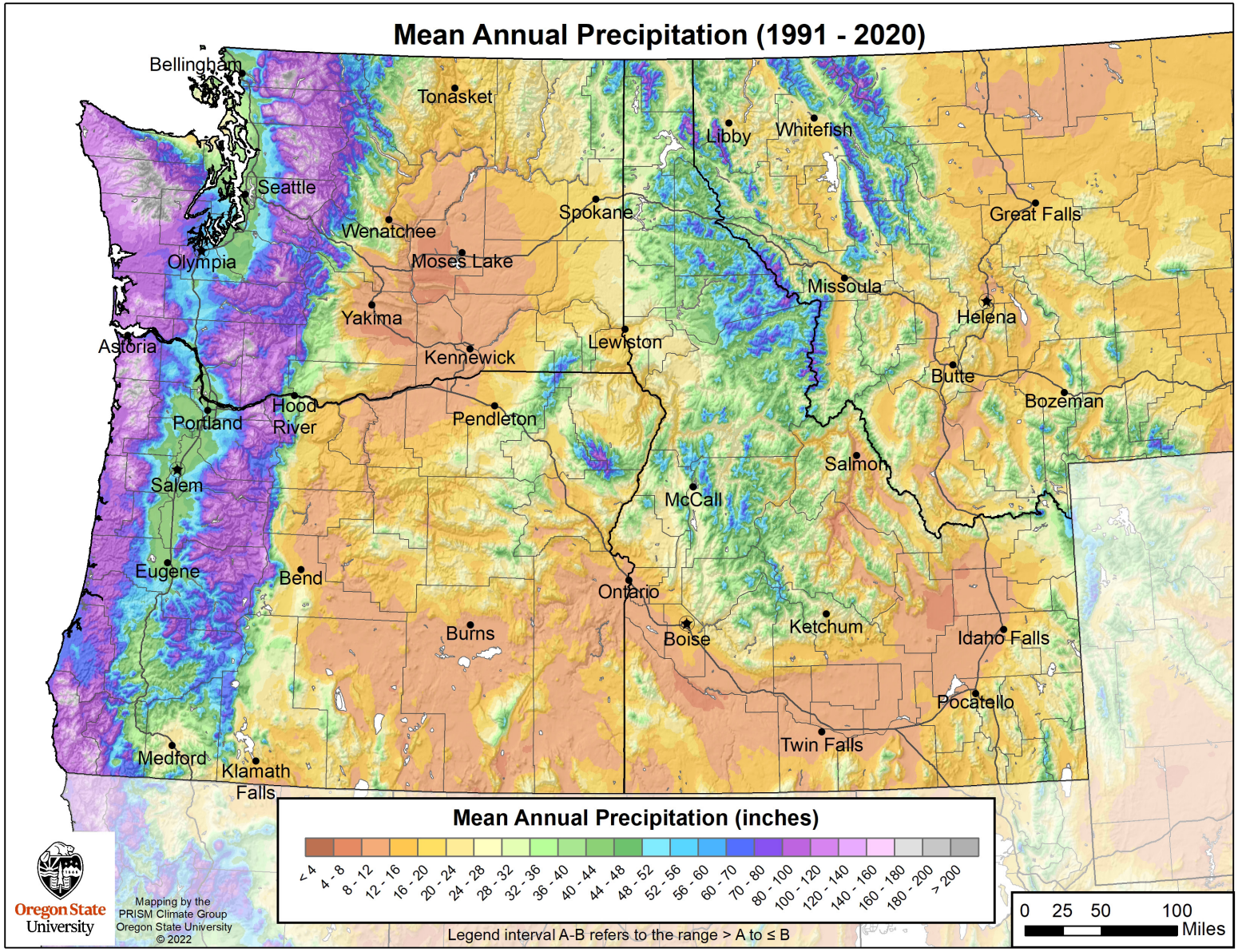

Figure 5. PRISM 1991–2020 normal annual precipitation across the Northwest.

After 24 years, the CoCoRaHS network of dedicated, volunteer observers has contributed to remarkable advances in understanding and application of meteorology and climatology. Municipal water managers use CoCoRaHS daily reports to assess supply and demand, while NWS River Forecast Centers use the daily reports as inputs to their flow prediction models. Stations with complete data over weeks, month, seasons, or years are of considerable value for agricultural applications such as the U.S. Drought Monitor, and for research on tropical storms and atmospheric rivers. The role of community science networks such as CoCoRaHS in improving the quality and detail of PRISM data cannot be overstated. Given the diverse use of PRISM data, community science weather networks have extraordinary, positive impacts throughout science and industry.

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How Community Science Benefits Everyone's Understanding of Snow and Water Resources

David F. Hill, Anthony A. Arendt, Gabriel J. Wolken, Katreen Wikstrom Jones, Ryan L. Crumley, Christina Aragon, and Emilio Mayorga

Learning About Snow and Water

Storage of water in the form of seasonal snowpack is a substantial component of the hydrologic cycle. The peak snow water equivalent (SWE) of the western United States has been estimated at 150 km^3 and that of North America at nearly 1700 km^3 (Mote et al. 2018, Wrzesien et al. 2018). An understanding of the distribution and evolution of this snowpack is important for many reasons, such as water resources planning (Li et al. 2017), hazard mitigation (Morin et al. 2020), ecosystem function (Winchell et al. 2016), economic benefit (Lundquist 2018), and hydrosphere and cryosphere modeling (Dutra et al. 2012). In the Pacific Northwest, snow and water are considerable hydrologic inputs. Oregon receives about 700 mm (28 in) of precipitation per year, averaged over the state, and Washington about 1000 mm (39 in) (Wang et al. 2016). In a typical year in Oregon, about 15 percent of that precipitation falls as snow.

Precipitation, evapotranspiration, streamflow, and other components of the hydrologic cycle can be measured or estimated in the field or with remote sensing or computer model simulations. Many of the field measurements of snow in the United States come from Snow Telemetry (Schaefer and Johnson 1992) (SNOTEL), Soil Climate and Analysis (SCAN), and Snow Course Data (SCD) networks operated by the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS), state snow-survey programs, and state departments of transportation. Some of the data from these sources have high temporal resolution (daily or sub-daily; e.g., automated snow pillow sites), whereas others have low temporal resolution (monthly; e.g., snow course). Field observations typically have low spatial resolution due to the costs associated with installation and maintenance of equipment. Because vehicular access generally is necessary for installation and maintenance, data from field observations also tend to under-sample high-elevation regions with complex terrain and few roads, especially four-season roads.

Remotely sensed data on snow can come from sources including airborne light detection and ranging (LIDAR) (Painter et al. 2016), unpiloted aerial vehicle (UAV) LIDAR (Jacobs et al. 2020), satellite LIDAR (Abdalati et al. 2010), visible-range imagery (Painter et al. 2009), and radar (Gusmeroli et al. 2014). The spatial resolution of these data can be quite high, e.g., on the order of 1 m (3 ft) for airborne LIDAR. The spatial extent of the data depends on the platform. Airborne measurements are local-to-regional, whereas satellite platforms can offer near-global coverage. A disadvantage of remotely sensed measurements is their comparatively low temporal resolution. For example, the Ice, Cloud, and Elevation Satellite (ICESat-2) mission (Neumann et al. 2019) captures an image of a given location every 91 days.

Simulation models (Essery et al. 2013) of snowpack processes can fill the spatial and temporal gaps in remotely sensed and field data. Because these models can make real-time predictions (Franz et al. 2008), they also have considerable operational value to diverse users, including avalanche forecasters and water managers. Models can be run at a wide range of spatial and temporal resolutions, and this flexibility means they can meet the needs of different stakeholders. Additionally, models exist on a spectrum of physical process representation: some models are simple and fast because they do

not directly simulate complex processes and instead use approximations, whereas other models are much more complex because they attempt to reproduce many or all of the processes occurring in the real world. In snow hydrology, energy balance models use either weather station data or modeled estimates of weather data to estimate energy fluxes and surface hydrologic processes. In these models, snow functions as an input (precipitation), a state variable (the entity being modeled), and an output (e.g., meltwater that runs off), and reliable snow information must be available for accurate model calibration and validation.

Public Participation in Snow and Water Programs

Public participation in the design and implementation of science, or *community science*, is a powerful means of increasing the scope and capacity of data collection. The number of permanent or fixed measurement stations is limited (Roy et al. 2012 , Crall et al. 2015). Members of the public, who usually are volunteers, can collect data at times and places not covered by fixed-station networks. Data from community scientists can be opportunistic in the sense that they are collected during unrelated activities that those individuals already had planned. Alternatively, data collection can be more directed in the sense that a participant designs and then follows a sampling program.

Compilation of physical environmental data from the public is far from new. For example, the Cooperative Observer Program (COOP) (Leeper et al. 2015) of the U.S. National Weather Service, which began in 1891, currently has more 11,000 contributors. The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) (Reges et al. 2016), launched in 1998, has grown into a large national network of observers who measure rainfall, snowfall, and hail. In the narrower context of seasonal snow and ice, there have been previous efforts to document snow cover with smartphones, and studies of how high-elevation mountaineers and alpinists can inform science on the basis of their field observations (Carey et al. 2016, Dickerson-Lange et al. 2016). The Global Learning and Observations to Benefit the Environment (GLOBE) program, which was launched in 1994 and is sponsored by the National Aeronautics and Space Administration (NASA), also has a protocol for snow observations. GLOBE observations tend to be associated with school programs and other home-based observers (similar to CoCoRaHS), and are generally representative of comparatively low elevations. Additional examples include efforts to collect data on precipitation phase (rain or snow) (Elmore et al. 2014, Arienzo et al. 2021).

Community science has a distinct set of opportunities and challenges. There is evidence that community science democratizes access to science and encourages scientific literacy (Bonney et al. 2016, Garbarino and Mason 2016, Mitchell et al. 2017). Additionally, the measurements can be comparatively low cost and have the potential to increase the spatial extent of data. The data are provided by volunteers who have the resources and skills (or obtain the skills with minimal training) to collect the data at home or in the field and transmit them to the project team. However, networks of data collected by the public can be decentralized and unstructured. Although some programs, such as GLOBE and CoCoRaHS, prioritize repeated measurements at the same locations, other programs, such as mPING (Elmore et al. 2014), are opportunistic and depend on decisions about the location and time of measurement that are made by the data collectors. A project team can offer suggestions about where and when to sample, but ultimately must rely on decisions made by the participants. Another challenge is controlling data quality. Protocols can be developed, tutorials provided, and quality control methods implemented post-submission, but ultimately, measurements are contributed by a diverse body of individuals with different levels of experience.

Learning from the Success of Community Snow Observations

The Community Snow Observations (CSO; communitysnowobs.org) project (Hill et al. 2018) was launched in late 2016 with the goal of developing a global, public network of individuals who collect and submit measurements of snow depth. Although anyone can participate, the project has prioritized participation by backcountry recreationists (e.g., skiers, snowmobilers, snowshoers) and snow professionals (e.g., ski patrollers, avalanche forecasters) who regularly visit high elevations with complex terrain. The primary goal of the CSO project is to evaluate how public participation in the collection of snow information can improve models of snowpack evolution and distribution (Crumley et al. 2021). Assimilation of research-grade measurements into snowpack models can improve the accuracy of those models (Largeron et al. 2020). A parallel goal of the CSO project is to engage the public in understanding and appreciating snow and water resources.

Below, we review the structure of and participation in the CSO project, including where, when, and how frequently participants contribute data. We then compare CSO data to a wide variety of snow products available from NASA and the National Oceanic and Atmospheric Administration (NOAA) to illustrate how community science data might be used to validate national and global snow data. We demonstrate how these community measurements improve scientists' ability to model snow, and illustrate the informational and educational products that are returned to participants.

Program Components

The CSO project has six primary components: a program to recruit and retain community scientists; instrumentation for measuring snow depth in the field; mobile and desktop applications for recording and submitting measurements; web services for gathering, displaying, exploring, and downloading participant data online; a modeling environment for assimilating public measurements into snowpack estimates; and a web-based application for visualizing model results in real time.

Participant Recruitment

The CSO project recruits three general categories of participants. The first category, which encompasses the majority of CSO participants, includes winter recreationists, such as backcountry skiers, snowboarders, snowshoers, and snowmobilers. These individuals participate in CSO as part of their recreation in the backcountry. We reach these participants through frequent presentations at snow and avalanche workshops, public meetings, and backcountry festivals hosted at ski areas. We also publish regularly in mass media and outdoor-oriented periodicals (Hill 2018, Lintilhac 2018, Menzel 2020). Our social media platforms and project website allow us to reach additional recreational participants. Our second major category of project participants includes snow professionals, such as avalanche forecasters and ski patrollers, who record snow depth as part of their own work. We reach these participants partly through articles about the project that we publish in trade magazines (Hill 2019, Hill and Redpath 2020). Our third category of participants is students in outdoor education programs that run winter classes. The students in these programs, which include Winter Wildlands Alliance's SnowSchool, Teton Science School, and National Outdoor Leadership School (NOLS), have diverse snow and backcountry knowledge.

To retain participants, our project team creates and disseminates snow products, such as images and animations, that are related to the snow conditions at the locations where participants collect and submit data. We also provide educational materials about snow science, including how snow is distributed and evolves, and snow data sources.

Field Snow Measurements

Complex measurements with specialized equipment can be a barrier to community science (Kleinke et al. 2018). Equipment costs may discourage new users altogether (Ryan et al. 2018), and even with low-cost instrumentation, lengthy measurements may deter participation by recreationists. Therefore, the CSO project focuses only on snow depth (Hs) rather than on variables that are more complex and time-consuming to measure, such as snow water equivalent (SWE) or albedo. The primary tool for CSO participants is an avalanche probe (Figure 1), a vital piece of safety equipment carried by backcountry snow enthusiasts. The design of probes varies among manufacturers, but most are 3 m long and have markings every 1 cm. They are compact, easy to deploy (similar to a segmented tent pole), and relatively low cost. Participants who do not have a probe can easily use a meter stick, or a tape measure affixed to a ski pole or other rigid pole. Protocols and tutorials on the CSO website explain how to measure snow depth properly. Key elements include making multiple measurements within a few square meters of undisturbed snow to obtain a reliable average depth for that area.

Figure 1. Measuring snow depth at Hatcher Pass, Alaska.

Recording and Submitting Measurements

CSO requires geolocated and time-stamped snow depth measurements. To maximize participation, CSO offers both mobile and desktop platforms for submitting these measurements (Figure 2). Mobile applications are the best choice for most participants because only a smartphone is required. Other participants, such as avalanche forecasters, who commonly record data in a field notebook often prefer a desktop application that allows them to submit data later from their home or office. The different platforms have different interfaces, enabling participants to choose the platform with which they are most comfortable. Multiple platforms also create redundancy, so data can be submitted when one platform is offline for maintenance or upgrades.

Four platforms currently are in use by the CSO project (Figure 2): Mountain Hub, CitSci.org, SnowPilot, and RegObs. CSO partnered with Mountain Hub (app.mountainhub.com), founded in 2015 as an adventure-sharing social platform, to customize its app for collecting and reporting snow information. Mountain Hub was acquired by Mammut Inc. in 2018 and then by CSO in 2020. This acquisition gives CSO control over the brand's social assets and the flexibility to introduce future improvements and upgrades for data collection by the public. The app (iOS and Android) allows users to quickly log snow depth and other parameters while in the field. If a user is out of cell phone range, the app will store the data and upload them when cellular or wireless service is reacquired.

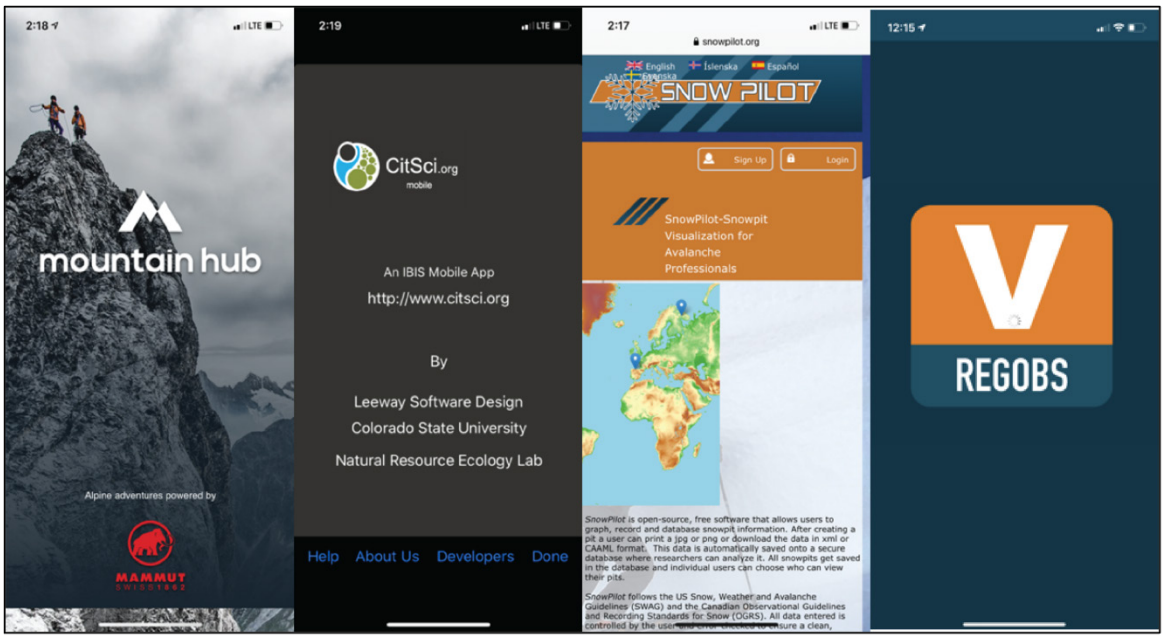

Figure 2. Platforms developed to support submission of data by Community Snow Observations participants.

CitSci.org, founded by the National Renewable Energy Laboratory (NREL) with support from the National Science Foundation, hosts approximately 1000 projects through its website and mobile application. Users can access the CSO project through the CitSci app (iOS and Android) and record data in the field. SnowPilot (www.snowpilot.org), a desktop application, is preferred by practitioners in the snow safety industry. Although much of the information that SnowPilot collects is beyond the scope of CSO, SnowPilot often is used to submit data on total snowpack depth. RegObs (www.regobs.no) is a public app developed in part by the Norwegian Water Resources and Energy Directorate. The app allows users to receive warnings and to submit observations about weather, natural hazards, and ground conditions, including snowpack depth. RegObs has global coverage and is available in many languages. [See *Addendum* below for an update on data submission platforms.]

Project Data Infrastructure

The CSO project has developed a data infrastructure for managing snow depth measurements submitted via any of the supported platforms. This infrastructure is hosted by a commercial cloud provider. CSO programs query snow depth data from the application programming interfaces, filter them on the basis of first-order data quality thresholds, and integrate them into a database. A web map application (Figure 3) allows the user to interact with, visualize, and download the data.

Snowpack Modeling

Many snow modeling efforts are intensive, watershed-level campaigns in which the watershed is heavily instrumented with sensors that provide information about weather and snowpack parameters. In contrast, the CSO project adopted an unstructured approach that is driven by where participants travel and measure snow; we welcome the "anytime, anyplace" approach to data collection by participants. The detailed model workflow (Figure 4) is described in Crumley et al. (2021). In brief, we use Micromet (Liston and Elder 2006b) and SnowModel (Liston and

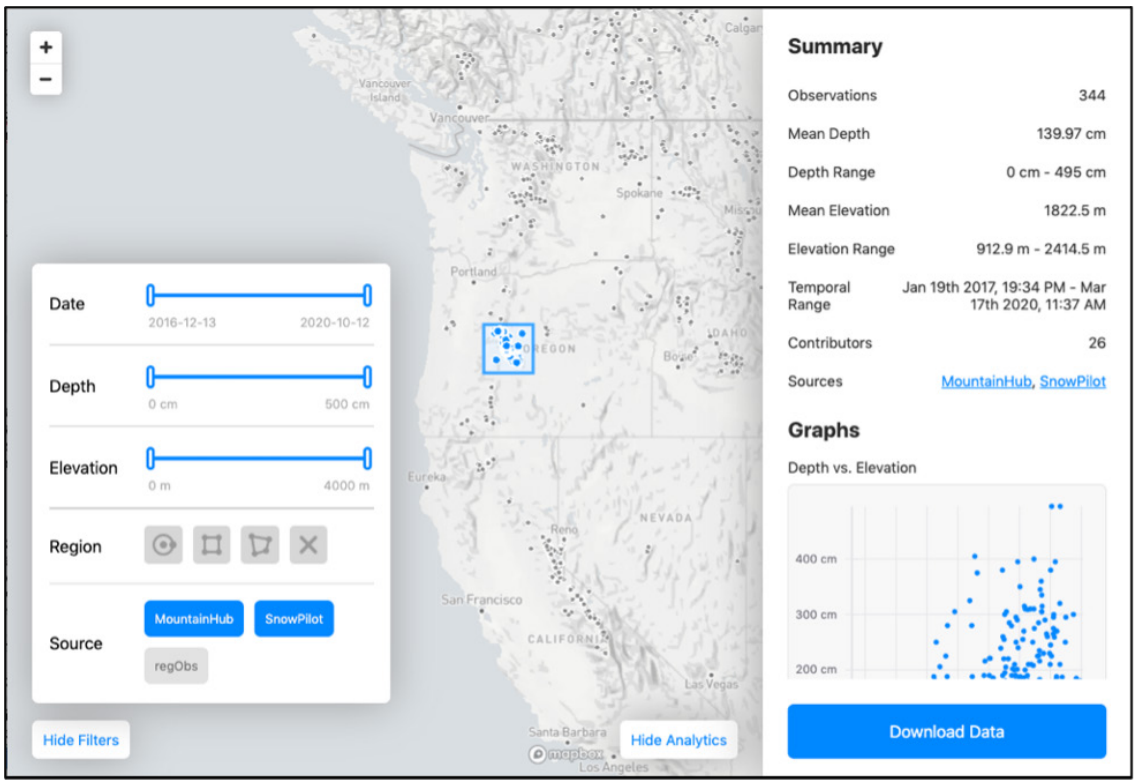

Figure 3. The Community Snow Observations web map application for visualizing, exploring, and downloading project data.

Elder 2006a), which are physically based models that interpolate weather data to a high-resolution (typically 30–100 m) model grid and evolve the snowpack, respectively. To rapidly set up new model applications, we have developed freely available scripts and digital notebooks that fully automate the acquisition of weather, terrain, and land-cover data for a prescribed area and time period; obtain weather and snowpack data for calibration; and automatically calibrate the model.

The next step in the modeling process is to use SnowAssim (Liston and Hiemstra 2008) to assimilate the data submitted by community scientists. The participants' measurements are compared to the model estimates and a set of corrections are created to adjust the model simulations on the basis of the observations. With our data-driven approach, the CSO project can implement model simulations in areas where project participation is high and where calibration data exist.

Real-Time Web Application

In many community science projects, participants function solely as data collectors, and there is little return of information from the science team to the participants. By contrast, the CSO project aims to deliver to participants high-value information, in real time, on snow distribution and other interesting variables. This delivery initially was

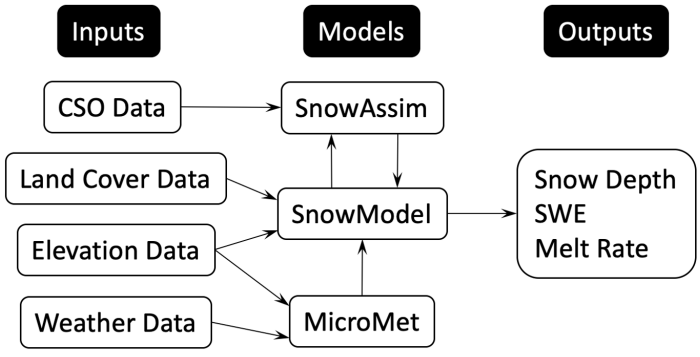

Figure 4. Workflow for snowpack modeling with assimilation of community science data.

accomplished in summer 2021 with the launch of MountainSnow (Figure 5) (www.mountainsnow.org). At this website, anyone can view and interact with the real-time modeling results in currently supported model domains. We regularly add new domains in areas where a high number of snow-depth submissions suggests a strong demand.

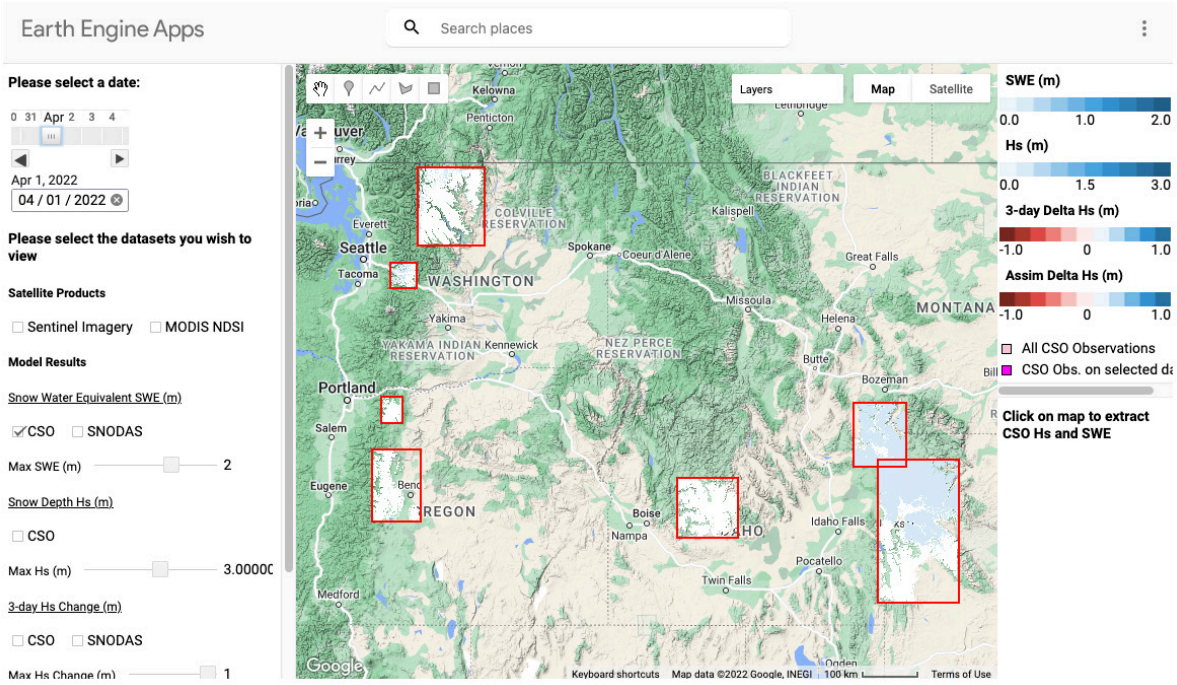

Figure 5. Sample image from the MountainSnow website.

At MountainSnow, users can view the CSO model data, satellite products related to snow cover, and other information such as the three-day change in snow depth. In addition to viewing maps of snow information, users can click on any location of interest to see the snow values there. Users also can view how participants' measurements improve the snow modeling process. We believe that this return on investment is a useful way to attract new participants and to educate, motivate, and retain current participants.

Results

Participation

From project inception through July 2022, more than 4000 unique participants submitted nearly 32,000 observations (Figure 6). Although CSO is a global program, the majority of our submissions come from the Northern Hemisphere, as reflected in the seasonality of observations. In Oregon, there have been nearly 900 measurements by 83 individual participants and in Washington, there have been over 600 measurements by 114 individual participants. The slight decrease in submissions during the 2019–2020 snow season can be attributed to the COVID-19 restrictions that curtailed access to many public lands, such as national forests and national parks, used by winter recreationists. The majority of CSO observations have been submitted by a small number of highly active participants: globally, 555 participants have submitted more than 10 measurements, 120 have submitted more than 50, and 49 have submitted more than 100. In Oregon, 16 participants have submitted more than 10 measurements, four have submitted more than 50, and three dedicated

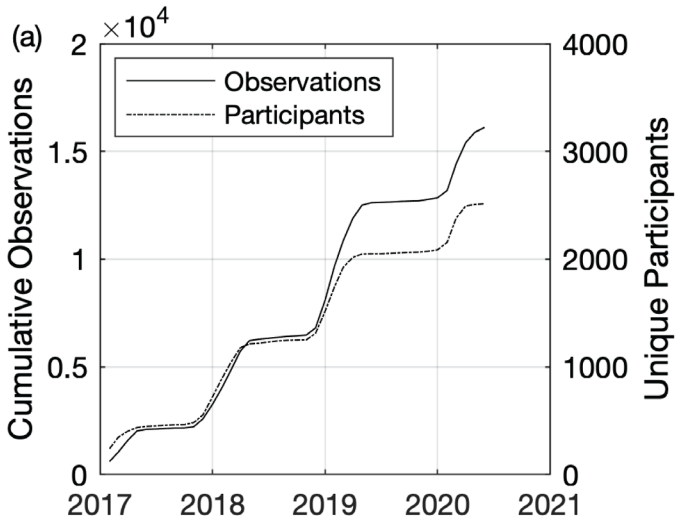

Figure 6. Cumulative number of Community Snow Observation submissions and number of unique participants since project inception.

participants have submitted more than 100 measurements.

To date, participants have submitted measurements from more than 30 countries, primarily within North America and Scandinavia (Figure 7). The geographic distribution of measurements is consistent with the fact that Mountain Hub, CitSci.org, and SnowPilot are based in the United States and RegObs was developed in Norway. Prior to the acquisition of Mountain Hub by CSO in summer 2020, CSO did not have email addresses of participants using that platform. Therefore, we have little information on the demographics (e.g., gender, age, race) of project participants. In the future, we hope to collect this information through participant surveys so that we can better understand who is choosing to participate in our program and aim to diversity the group of participants.

Inclusion of CSO Data in Snowpack Modeling

A complete demonstration of how the inclusion of community snow-depth data improves snow model estimates is available in Crumley et al. (2021). Here, we provide an example from a SNOTEL site in the Wasatch Mountains east of Salt Lake City, Utah (Figure 8). Snow water equivalent (SWE) varies throughout the water year, from 1 October (day 0) through 30 September. Day 180 corresponds to about 1 April. Data from the SNOTEL site demonstrate that snow accumulates steadily until early April, and then melts rapidly (red line). When we calibrate our model and do an "open loop" run, which does not include participant data, the model underestimates the snowpack (blue line).

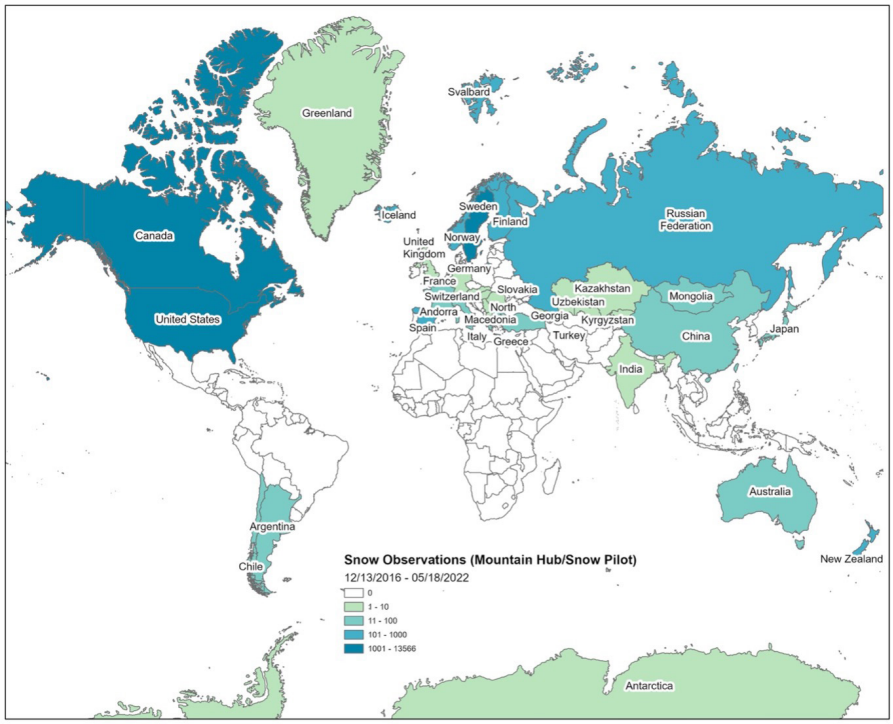

Figure 7. Geographic distribution of CSO submissions from 2016–June 2022. Shading reflects the number of submissions received from each country.

There are many reasons for the underestimate, including unresolved physical processes, biases in weather forcing data, and errors in the numerical modeling process.

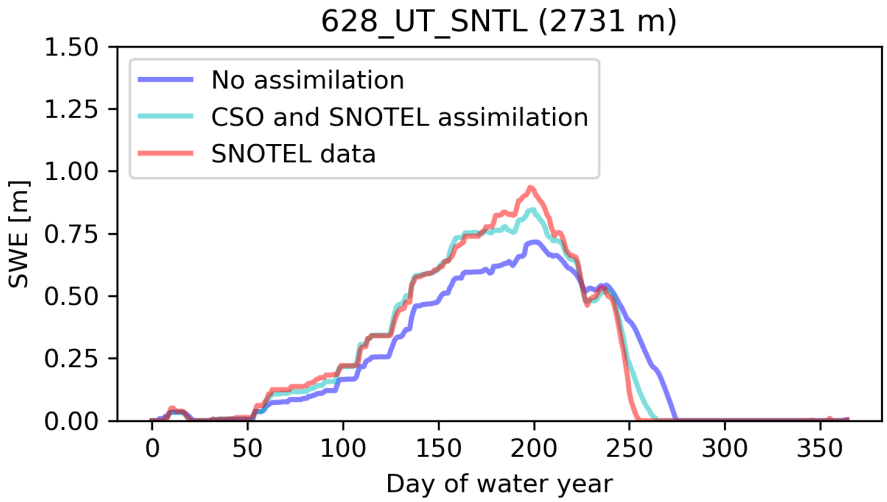

Figure 8. Example of improvements in a model of snow depth at a SNOTEL station in the Wasatch Mountains, Utah, enabled by the assimilation of participant observations.

When we include (or assimilate) both the local CSO data and the SNOTEL data (excluding data from this validation station) in the model, the model output is a close match to the data (cyan line). Assimilation of participant data improves our modeling (Figure 8). We continue to compare the contributions to improvement in model accuracy from CSO data and SNOTEL data. This is valuable because SNOTEL sites are sparse. Community participation can fill these geographic gaps in data and ensure that we obtain the best possible model results for all locations. CSO observations markedly increase the diversity of terrain for which in-situ observations are available (Figure 9).

Comparison of CSO Data with Satellite Data

A variety of snow products at varying spatial and temporal resolutions are provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) (Hall et al. 1995) and VIIRS (Visible Infrared Imaging Radiometer) (Key et al. 2013) satellite missions. As one example, the MOD10A1 product (Version 6) is a 500 m, daily product with a period of record that began in February 2000. One of the variables provided by the MOD10A1 product is the Normalized Difference Snow Index (NDSI). Although there is regional variability in the NDSI value associated with a snow-covered area, an NDSI value of 40 percent is an accepted global standard (Riggs et al. 2015).

CSO data points, which are typically from high-elevation locations with complex terrain, provide a unique comparison with the MOD10A1 product. Unlike CoCoRaHS or NASA GLOBE, which frequently report both zero snow depths and positive snow depths, most CSO data reflect positive snow depths, and often considerable snow depths. Therefore, we hypothesized that the location and time of CSO submissions are reliable indicators of snow-covered areas. To evaluate this hypothesis, we extracted the NDSI values at CSO submission locations for two seasons. Of the 4000 CSO measurements, 1298 could be associated with NDSI values; the balance appeared to be made under cloudy skies that prevented satellite observations. Our results were consistent with the assumption that NDSI >40 indicates a snow-covered region (Figure 10). Only 6 percent of the CSO measurements have an NDSI less than this threshold value.

Most of the CSO points with low NDSI have non-zero snow depth. It is possible that a user was entering a no-depth measurement (which is valid, if infrequently reported) but mistyped and entered a non-zero depth. In this case, MODIS correctly reported NDSI = 0, and the erroneous CSO point

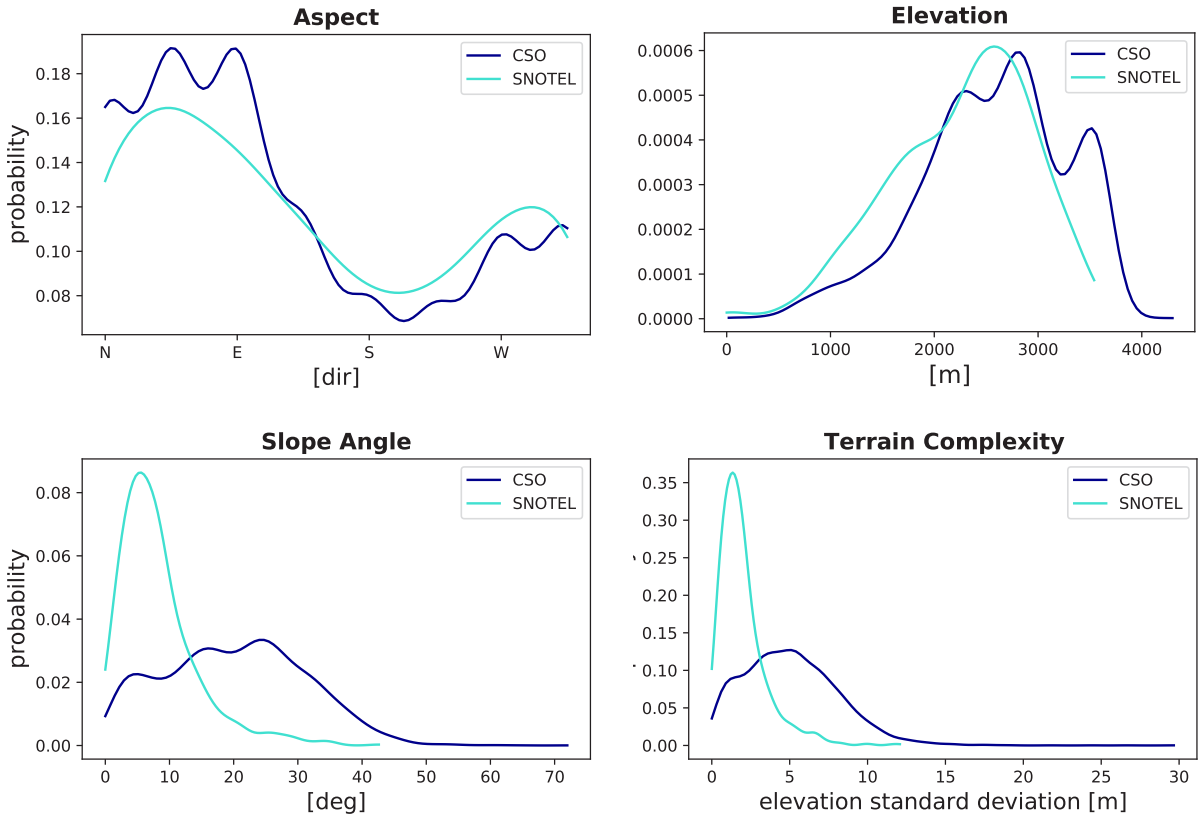

Figure 9. Probability density functions of terrain features (aspect, slope, elevation, and terrain complexity) associated with individual CSO observations submitted from 2016 through 2021 and the locations of SNOTEL stations across the western United States. We extracted elevation and calculated aspect, slope, and terrain complexity scores for CSO and SNOTEL locations from the 10-m resolution National Elevation Dataset. Slope and aspect were computed with the four connected neighbors of each pixel corresponding to the location of the CSO observation or SNOTEL site. The terrain complexity metric was calculated as the standard deviation of the 3x3 square kernel surrounding an observation or station location.

could be flagged as an outlier. A second possibility could be a geolocation error: the CSO participant correctly reported non-zero Hs, but the coordinates were incorrect and corresponded to a location with no snow depth (NDSI = 0). A third possibility is related to variability at sub-grid resolution. A MODIS grid cell with an NDSI value of 0 should indicate a snow-free land surface over the 500 m grid cell. However, several processes, including wind redistribution and differential melting of snow, can lead to patches of snow within an otherwise bare area. If a grid cell is mostly bare (say near the snow line), then a valid non-zero snow depth measurement could accompany a NDSI = 0 value.

All of the CSO data points with NDSI = 0 were in high mountain locations during snow season. Therefore, the first two explanations above are unlikely. To better understand the low NDSI values, we aim to require that future CSO measurements include photographs of the surrounding area (to gauge snow cover; these photographs currently are optional). Additionally, the CSO science team plans to pursue gridded, intensive measurements spanning entire MODIS grid cells. This will help determine the degree to which MODIS data could be used to identify outlier CSO points, or the degree to which CSO data might help to refine the MODIS results.

Are We Giving the Public What They Want?

Much of CSO's effort over the first few years was focused on a study site near Thompson Pass, Alaska. This intensive focus allowed us to work on a proof of concept and to develop all of the modules needed to fully implement a community science modeling project. Since that time, our emphasis on open science, public engagement, and collaboration between the science team and the public has led to steady growth of the project. We receive frequent comments from individuals and educational programs that the simple process of observing snow teaches them a great deal about how snow changes from place to place and time to time.

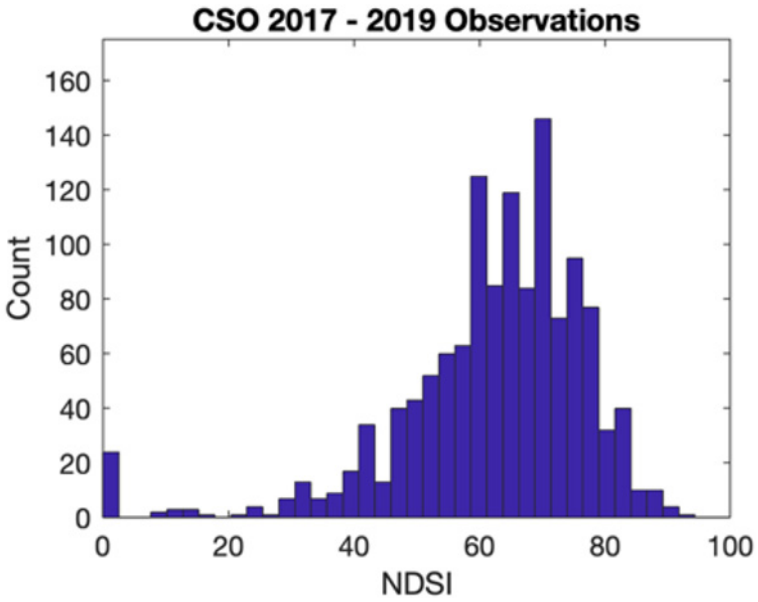

Figure 10. Normalized Difference Snow Index (NDSI) values corresponding to the locations and times of CSO observations. Data are for the 2017–2018 and 2018–2019 snow seasons.

The science team has learned a great deal from participant feedback. For example, we sometimes hear concerns about personal and location privacy. In the interest of transparency and accessible science, all data submissions appear on our project website. Some participants (or potential participants) do not want to reveal their locations as a matter of personal preference (personal privacy). Other participants do not want to attract more people to their favorite locations (location privacy). Accordingly, privacy is a real barrier to participation. When CSO began, we had little control over Mountain Hub and privacy settings. Now that CSO owns Mountain Hub, we hope to design a private mode in which submissions of snow depth will be available to project staff but will not be displayed online or otherwise be made public.

Another barrier to participation is regional differences in preferred sources of snow information. Most countries with snow environments have a national agency that is tasked with avalanche monitoring, mitigation, and education. Some countries, such as the United States, have regional agencies that are similarly tasked. Many of these agencies have their own data collection programs and protocols, although the focus (e.g., avalanche stability, snow pit profiles) usually is different from CSO's sole focus on snow depth. Some agencies are resistant to introducing a new app (Mountain Hub) that they feel will lead to a decrease in submissions to their own programs. The CSO program is working to build a culture of data sharing and cooperation that we hope will alleviate concerns about competition for data.

Among our ongoing goals are to better quantify uncertainty in data quality and reliability (Hill et al. 2019, Crumley et al. 2021) and to offer tools and training to minimize erroneous observations. These goals are consistent with NASA's recent efforts (Amos et al. 2020) to formalize data standards and data quality for observations from public participants. Sources of error in the CSO project include observers mistyping an entry on their mobile device; submission of data via the mobile

app from a physical location other than where they were collected, causing the coordinates of the measurement to be incorrect; and poor selection of measurement locations (for example, in an area of significant scour, deposition, or disturbed snow). We can mitigate the first source of error by asking (or eventually requiring) participants to include a photograph of the depth measurement on their measurement device. We can mitigate the second by reinforcing through tutorials that measurements submitted via the mobile app must be submitted at the observation site. Additionally, since taking possession of the Mountain Hub app, we have made numerous improvements to its positional accuracy. We can mitigate the third source of error by continuing to provide tutorial videos on our website that enable participants to recognize ideal measurement locations. We are also developing data filters that automatically screen for erroneous depth measurements by comparing the submissions to MODIS-derived and other snow products.

We believe that the future of community science in the context of water and snow is bright. Science is advanced by access to new and unique data, and public understanding of and appreciation for water resources is advanced through active participation and learning. The flexible CSO collaboration gives participants control over their level of participation, and therefore their experience. The project also readily can grow. Because we develop models in areas with strong participation, the future of the project is in the hands of the public. If you are intrigued, please consider exploring the many community science projects related to climate and water that are available to you.

Addendum

Between submission of this contribution and publication, the data submission platforms available to participants in the CSO project changed. The Mountain Hub app, website, and social media channels have been retired. In September 2022, the CSO team partnered with Propagation Labs (www.propagationlabs.com) to make use of their Snow Scope app (available for iOS and Android). This app (Figure 11) is an extremely fast and easy way to log snow depth measurements, and the CSO team recommends this app for all its recreational users. As with Mountain Hub (and the other platforms) previously, all data submitted via Snow Scope automatically will flow to the CSO website and database.

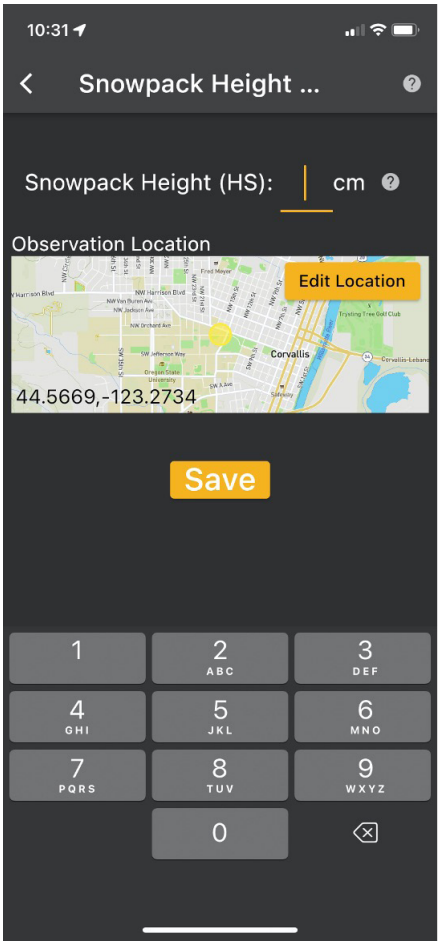

Figure 11. View of the Snow Scope app developed by Propagation Labs.

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Community Observers' Distinct Role in Advancing Meteorology and Climate Science

Meghan Collins, Keith Jennings, Monica Arienzo, Benjamin Hatchett, and Anne Nolin

In many regions, community observers have both on-the-ground access to diverse geographic areas and the ability to discern complex weather and climate patterns, or anomalies in those patterns, in a meaningful way. Answering many questions in meteorology, climatology, and climate change requires this combination of access and skills. High-resolution observation of weather over large areas, which can inform climate science, requires access to places from backyards to the backcountry, including places where deployment of weather stations and similar infrastructure is not feasible. Even more importantly, community observers can provide local and historical context for weather and climate phenomena and distinguish changes in these phenomena that technology or analyses have not yet recognized. Here, we describe how the nexus among community observers, professional scientists, and technology advances understanding of weather and climate.

Human observation of environmental phenomena has a long history. Local and traditional knowledge, collected over generations, helped people to survive and thrive worldwide and as climate changed. As the field of science has evolved, so has the spectrum between community observer and professional scientist. In the last ~150 years, Western science has become increasingly professionalized, creating a larger divide between professional scientists and non-professionals, often marginalizing the role of the latter (Miller-Rushing et al. 2012). However, a more formal role for community observers has grown in recent decades, along with formal names for their contributions to science, such as public participation in scientific research, citizen science, community-based monitoring, and community science. The term *citizen science*, first used in the mid-1990s, was intended to evoke the idea of scientific citizenship (Bonney 2021): civic involvement in science, or participation in science without the need for credentials (Shirk et al. 2012). But as many have pointed out (e.g., Cooper et al. 2021), the word *citizen* can be exclusionary and possibly reinforces a pattern of limited representation in science. *Community science* describes the role of community members in guiding research questions, analysis, and applications of science. Here, we use *community observer* because the contributors to the programs featured here track weather and climate phenomena to advance research questions driven by the scientific community. Dialogue about terminology and resulting changes to the culture and conduct of science (e.g., Pandya 2019) has led to acknowledgment of observers' role in generating knowledge, especially as technology evolves and as specialized fields of science increasingly require extensive training.

A broad range of technologies and extensive infrastructure have been central to many of the advances in weather and climate science during the last century. Weather and climate can be observed through extensive networks of instruments, such as weather stations equipped with thermometers, rain gauges, and sensors to track humidity, insolation, and atmospheric pressure. Examples include Snow Telemetry (SNOTEL) and Remote Automated Weather Stations (RAWS). These networks yield data from which models are created. Weather and climate also can be observed through remote sensing, which includes weather radar (e.g., Doppler) to locate precipitation and storm activity; aircraft; and satellites that track cloud cover, land surface and air temperatures, and wind. Some examples of these satellites include the U.S. National Weather Service's Geostationary Operational Environmental Satellite (GOES)-East and the CloudSat and Global Precipitation Measurement (GPM) systems of the National Aeronautics and Space Administration (NASA).

Remote sensing products also contribute to numerical forecasts of weather and climate, which require assimilation of extensive data. Advances in machine learning may overcome some limits to conventional climate models (Huntingford et al. 2019, Schultz et al. 2021, Rolnick et al. 2022). For example, deep learning is among the methods used to forecast weather beyond two weeks (Weyn et al. 2021) and to predict severe weather such as hailstorms (Gagne et al. 2019). Nevertheless, scientists and keen observers must work closely with evolving technological tools to answer major questions in weather and climate science.

Mountain Rain or Snow

Mountain Rain or Snow illustrates our belief that the triad of scientists, community observers, and technology is a powerful means of addressing weather and climate challenges. Human and natural systems are adapted to seasonal patterns of rain and snow (Barnett et al. 2005). The warming-induced shift from snow to rain challenges water supply planning, water availability, and ecosystems (e.g., Livneh and Badger 2020). However, despite years of research, it remains challenging to predict whether precipitation will fall as rain, snow, or mixed (Harpold et al. 2017). The freezing point of water is an unequivocal 0°C (32°F), yet contemporary hydrologic, land surface, and climate models and remote sensing products, which inform water budgets and hydrologic models, do not accurately partition precipitation into rain and snow near freezing (Jennings et al. 2018, Skofronick-Jackson et al. 2019).

To improve satellite measurements and models for detecting rain, snow, and mixed precipitation, the Mountain Rain or Snow team has been working closely with community observers to crowdsource visual observations of precipitation phase (Arienzo et al. 2021). Since 2019, we have worked with over 1400 participants to track more than 15,000 observations of rain, snow, and mixed precipitation (Figure 1).

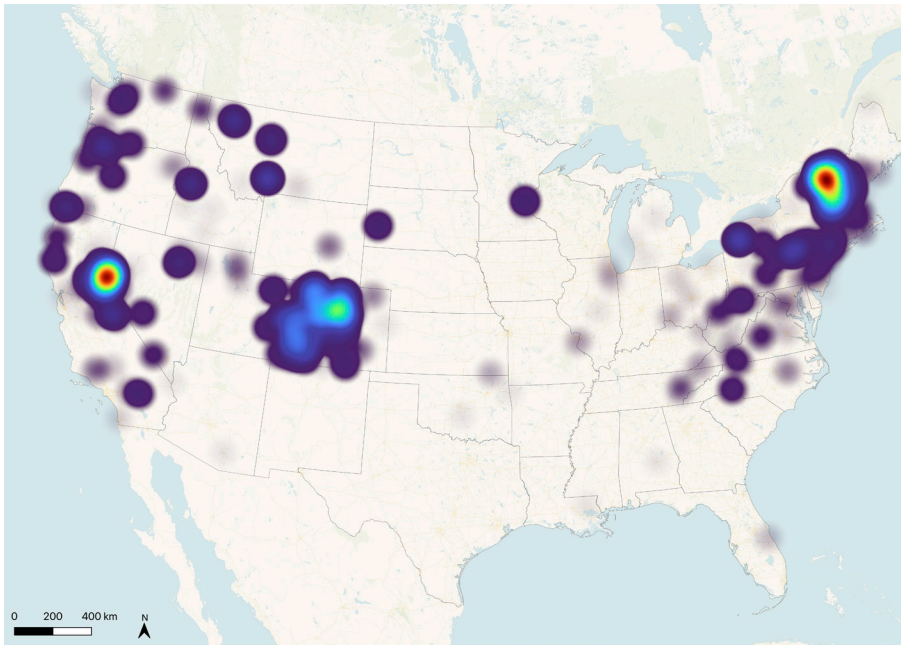

Figure 1. Distribution of Mountain Rain or Snow community observations in the continental United States during the winter of 2021–2022. Warmer colors indicate a greater number of observations. Our team analyzes observations on the basis of ecoregions.

The large number of ground-based observations compiled by Mountain Rain or Snow adds to surprisingly few other direct observations of rain and snow. In the United States, the largest network of precipitation phase reports consists of airports that contribute to the National Oceanic and Atmospheric Administration's Local Climatological Dataset. These data are useful, but typically are collected in flat, low-elevation areas, and do

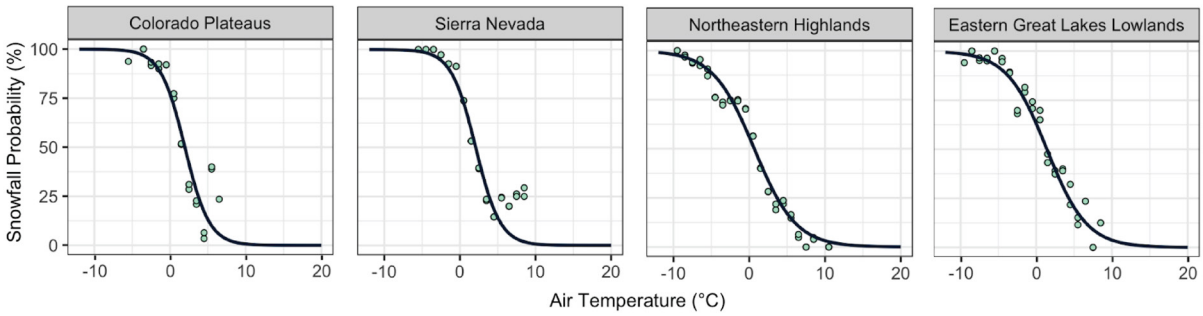

Figure 2. Probability curves produced by applying a binary logistic regression model to community observations submitted to Mountain Rain or Snow from 2021–2022. The probability of snowfall as a function of air temperature varies among U.S. Environmental Protection Agency Level III Ecoregions.

not represent higher elevation, more-complex mountain environments. As a result, they contribute little to understanding of hydrometeorological processes in the areas where the distinctions between rain versus snow matter most, and lead upland regions to rely on models and products derived from remote sensing.

Accurately tracking precipitation at the freezing point across a range of elevations and climatic zones is relevant because the hydrologic outcomes of rain and snow are fundamentally different. Rain is more ephemeral, generally infiltrating or running off soon after reaching the ground. Snow accumulates into seasonal snowpacks that act as natural, in situ reservoirs. Snow also cools the planet by reflecting incoming solar radiation. Humans, particularly in cold and temperate regions, depend on reliable seasonal cycles of snow accumulation and melt. Increasing air temperatures are driving declines in mountain snow accumulation, earlier snowmelt, and increases in the risk of floods caused by rain falling on snow. The greatest uncertainty in whether precipitation is rain or snow is near freezing.

Mountain Rain or Snow's community observations and analyses are improving NASA's GPM-derived estimates of whether precipitation is rain, snow, or mixed, and the probability of snowfall as a function of air temperature (Figure 2). Probability curves built with community observations of precipitation illustrate why a strict 0ºC threshold is not accurate for predicting whether precipitation is falling as rain or as snow.

As a result of the true heterogeneity in snowfall probability, predictions of precipitation phase from NASA GPM have varying levels of accuracy. The accuracy of NASA GPM-derived predictions of precipitation phase diverges from quality-controlled observer data from 0–8ºC (32–46˚F) (Figure 3).

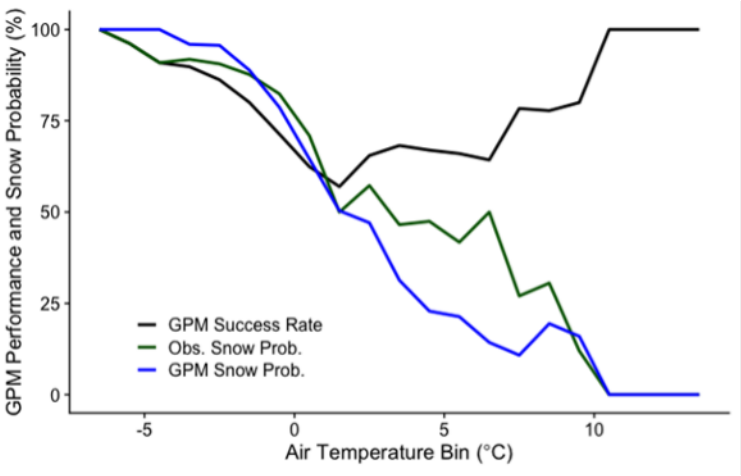

Figure 3. Divergence in the probability of snow during the winter of 2020–2021 according to quality-controlled, ground-based community observations versus Global Precipitation Measurement (GPM) satellites.

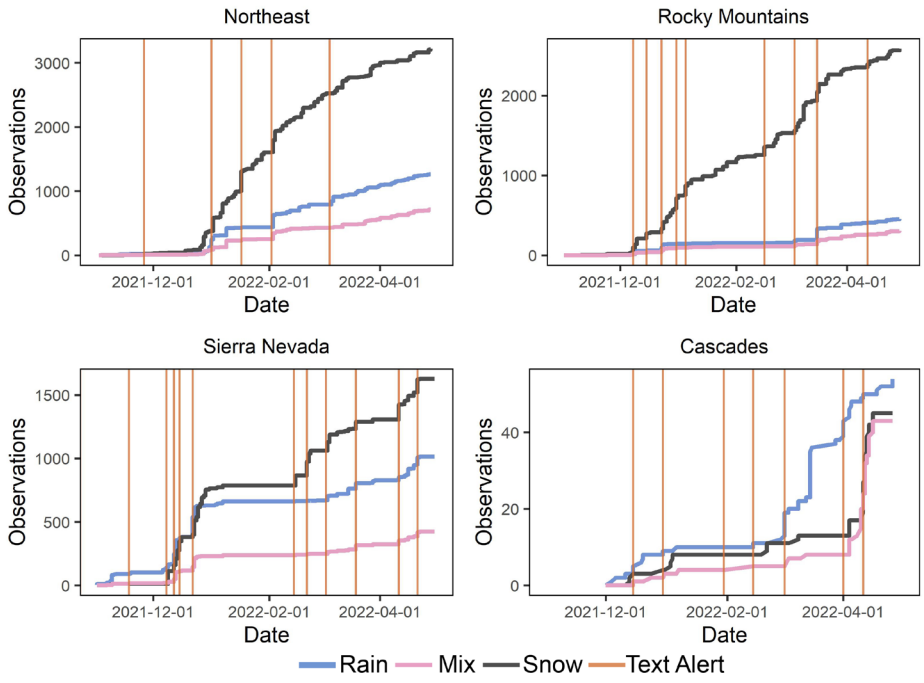

Figure 4. Text messages sent directly to Mountain Rain or Snow observers to encourage submission of observations of rain, snow, or mixed precipitation. The timing of text alerts is indicated by vertical lines.

In addition to scientific contributions, Mountain Rain or Snow seeks to advance collaboration with community observers via an ecoregion-specific, two-way text communication system. We send alerts when a local storm is approaching, and we respond to observer questions in real time to improve the user experience and the quality of the data submitted. In a recent survey of Mountain Rain or Snow observers, 82 percent of respondents (n = 415) indicated that the alerts helped them know when to submit observations of precipitation. The survey responses were consistent with the data submission trends, which indicated that text alerts increased the number of observations of the following storm (Figure 4).

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Wildfire

The wildfires that occurred across Oregon in September 2020 galvanized public attention on changes in the patterns, causes, and consequences of wildfires in the state, across the western United States, and worldwide. Rupp and Holz begin this section by exploring recent advances in understanding of wildfire trends and mechanisms. For example, evidence rapidly is accruing that extreme aridity enables large fires that expand quickly and can be remarkably difficult to contain. Social phenomena also affect the probability, locations, and timing of wildfires, especially via inadvertent human-caused ignitions. Nevertheless, as Kalashnikov explains in the second contribution to the section, a majority of wildfires east of the Cascade Range in Oregon continue to be caused by dry lightning during spring and summer.

The U.S. Department of Health and Human Services emphasizes that personal health literacy is a social risk, and organizational health literacy is a social determinant of health (health.gov/healthypeople/priority-areas/social-determinants-health/literature-summaries/health-literacy). Personal health literacy refers to individuals' ability to find, understand, and use information and services to inform their health-related decisions and actions, whereas organizational health literacy refers to the extent to which organizations equitably enable individuals to find, understand, and use such information and services. Accordingly, as a complement to the focus in *Public Health* (this volume) on the responses of human health and the healthcare system to wildfire smoke, two contributions to this *Wildfire* section examine public responses to and preparation for wildfires. Boudet and colleagues report on the results of a survey of Oregonians' behaviors related to protection of their health, property, and communities; their attitudes and beliefs about relations between wildfires and climate change; and their support for policies designed to adapt to or mitigate climate change. Coughlan and colleagues present the outcomes of a separate survey, implemented in English and Spanish, that examined Oregon residents' concerns, communication needs, and responses to wildfire smoke during the 2020 wildfire season. Both efforts contribute to the foundation for tracking future changes in health literacy and policy preferences.

The survey that Coughlan and colleagues describe was informed in part by collaboration with the Smoke Ready Communities working group. This group, convened by Oregon State University Extension Forestry and Natural Resources faculty members in January 2021, aims to identify mechanisms and media that best serve Oregonians affected by wildfire smoke and displaced by wildfire, educational information and resources, and how Oregonians access information about smoke. After its launch, the group rapidly expanded to include colleagues from other units at Oregon State University, University of Oregon's Institute for a Sustainable Environment and its Ecosystem Workforce Program, Portland State University, Oregon Department of Environmental Quality, Oregon Health Authority, Sustainable Northwest, county emergency management professionals, and other practitioners of smoke-risk mitigation. The group serves as a community of interest in which public health and environmental quality researchers and outreach educators connect to explore needs and opportunities. Participants are reviewing existing educational materials and developing new materials to fill gaps in information and education, and they are developing processes to use Oregonians' preferred media and outreach mechanisms to better address smoke-related education and communication needs.

Wildfire Trends and Drivers

David Rupp and Andrés Holz

The 2020 Labor Day Wildfires

No wildfire event has affected or threatened as many Oregonians as did the numerous wildfires that erupted across western Oregon on Labor Day (7 September) 2020. Those wildfires eventually burned nearly 4,000 km^2 (~1,500 mi^2), mostly forested, including more than 11 percent of the Oregon Cascade Range. The area burned in the western Cascade Range in 2020 equaled or surpassed that in any other year for which records are reliable (Abatzoglou et al. 2021c, Reilly et al. 2022). One of the strongest and driest easterly winds recorded since 1948, combined with vegetation that desiccated over the unusually hot and dry preceding weeks, drove the rapid growth of the fires (Abatzoglou et al. 2021c, Mass et al. 2021, Evers et al. 2022). The fire weather, as measured by a combination of heat, aridity, and wind that is consistent with expansion of wildfire, was more extreme over large areas of western Oregon than recorded since 1979 (Hawkins et al. 2022), although probably similar to fire weather during other major wildfires in western Oregon before and since European colonization (Abatzoglou et al. 2021c, Reilly et al. 2022).

Trends in Wildfires

Although the 2020 Labor Day fires were singular and defining in Oregon's history, they were among many wildfire outbreaks throughout the western United States in 2020. That year's extraordinary fire season was characterized by a large number of fires that grew extremely rapidly over a period of one to a few days, enabled by unusually high aridity (Higuera and Abatzoglou 2021, Coop et al. 2022).

The Labor Day fires also were one event in a regional trend. Total annual area burned in Oregon has increased during the last 35 years (Figure 1). Despite the considerable area burned by the Labor Day fires, the area burned in other recent years (e.g., 2012), mostly in southwestern and eastern Oregon and encompassing all land-cover types and fire regime groups, was slightly higher (Figure 2). Across the western United States, the frequency of large wildfires has increased faster than that of small wildfires in forested areas (Juang et al. 2022), and large forest fires have become near-annual in the northwestern United States (Halofsky et al. 2020). The annual area of shrubland burned, roughly half of the total area burned, has also increased, although its proportion of the total area burned has decreased (Li et al. 2021).

As aridity has increased, wildfires have spread into higher elevations that previously were cool and moist enough to deter fire expansion (Alizadeh et al. 2021). In the Cascade Range and Blue Mountains, for example, wildfires moved upslope at rates of 10 and 12 m (33 and 39 ft) per year, respectively, from 1984–2017. Reductions in snowpack depth also contributed to the upslope movement (Mote et al. 2018). Additionally, the larger fires in the western United States have generated taller plumes of smoke and injected a greater volume of fine particulate matter ($PM_{2.5}$) at high altitudes, increasing long-range transport of $PM_{2.5}$ and posing a health hazard to larger numbers of people (Wilmot et al. 2022). The population exposed to persistent extreme $PM_{2.5}$ and ozone levels in the western United States increased by 25 million person-days per year over the period 2001–2020 (Kalashnikov et al. 2022). In the northwestern United States, wildfire smoke accounted for more than 50 percent of $PM_{2.5}$ during 2017 and 2018, an increase from about 20 percent during the previous decade (Burke et al. 2021). Deposition of black carbon from large wildfires also increased the rate of snowmelt at high elevations (Uecker et al. 2020).

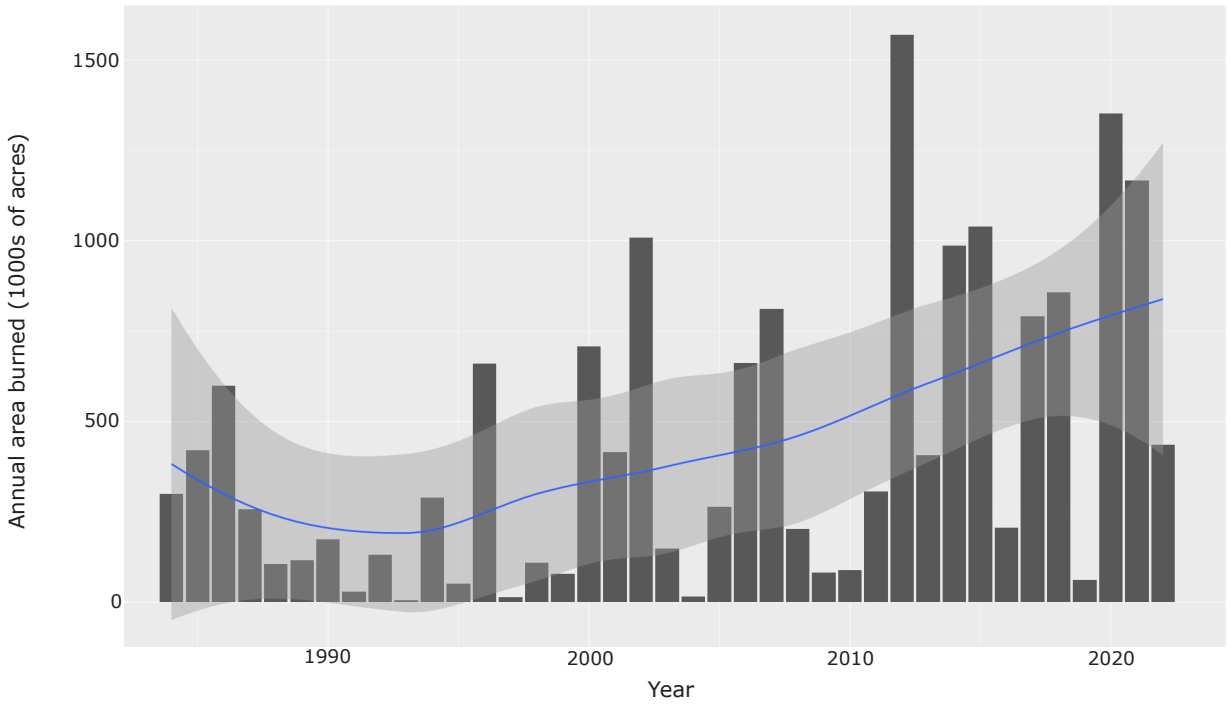

Figure 1. Annual area burned in Oregon from 1984–2022. Fires smaller than 988 acres (400 ha) were omitted. Data from Eidenshink et al. 2007 updated to October 2022 (www.mtbs.gov).

Cooler temperatures overnight typically alleviate extreme fire weather. However, an increase in nighttime temperatures (e.g., Cox et al. 2020) caused persistent nighttime fire activity across the conterminous United States, mainly concentrated inside large wildfires, from 2003 through 2022 (Freeborn et al. 2022). Nighttime fire intensity also increased globally from 2003 through 2020, driven by warmer and drier nights (Balch et al. 2022).

Regional and Global Trends in Aridity and Fire Weather

From 1979 through 2019, the duration of the fire weather season in forests of Washington, Oregon, Idaho, and California increased by 43 percent, and the annual number of days when fire danger was extreme increased by 166 percent (Jones et al. 2022). Widespread drought has led to high fire danger across much of the western United States in many recent years, further straining wildfire-suppression resources that must be shared across the region (Podschwit and Cullen 2020, Abatzoglou et al. 2021b).

These regional trends are part of the global trend of increasing fire danger over the last four decades (Ellis et al. 2022, Jain et al. 2022, Jones et al. 2022, Richardson et al. 2022). Most of the world's ecoregions became drier during this time (Ellis et al. 2022). Worldwide, fire weather became more extreme, primarily due to decreases in relative humidity (Jain et al. 2022).

Atmospheric Drivers of Wildfire

Northward displacement and weakening of the polar jet stream during summer may increase the probability of extreme wildfires (Jain and Flanagan 2021). Persistent atmospheric pressure ridges over North America that are coincident with the shift in the polar jet stream appeared to increase aridity and the probability of wildfires, particularly across more northern latitudes (Justino et al.

2022, Sharma et al. 2022). Arctic amplification may contribute to the development of these high-pressure ridges, which in turn may increase the frequency of summer heat waves and fire weather in the western United States during autumn (Zou et al. 2021; also see *Arctic Amplification*, this volume).

Contribution of Anthropogenic Emissions to Recent Fire Weather

Increases in global concentrations of greenhouse gases since the mid-1800s have increased the likelihood of extreme autumn fire weather by an estimated 40 percent over the western United States and about 50 percent over western Oregon (Hawkins et al. 2022). Autumn fire weather in western Oregon that would have occurred, on average, every 20 years during the pre-industrial era had a 13-year average return interval during the last several years. The higher likelihood of extreme fire weather was attributed to decreased vegetation moisture content during autumn and warmer temperatures during dry wind events, although emissions appear to have little effect on the frequency of easterly, downslope winds that can drive explosive fire growth (Hawkins et al. 2022). Natural variability in atmospheric circulation accounted for an estimated 32 percent of the positive trend in atmospheric vapor pressure deficit (VPD)—a variable positively correlated with wildfire area—over the western United States from 1979–2020, and anthropogenic emissions for the remaining 68 percent (Zhuang et al. 2021).

Future Wildfire

Numerous projections of future wildfire or fire weather and ignitions in the western United States have been made over the last few years, including two focusing on regions in Oregon. Projected

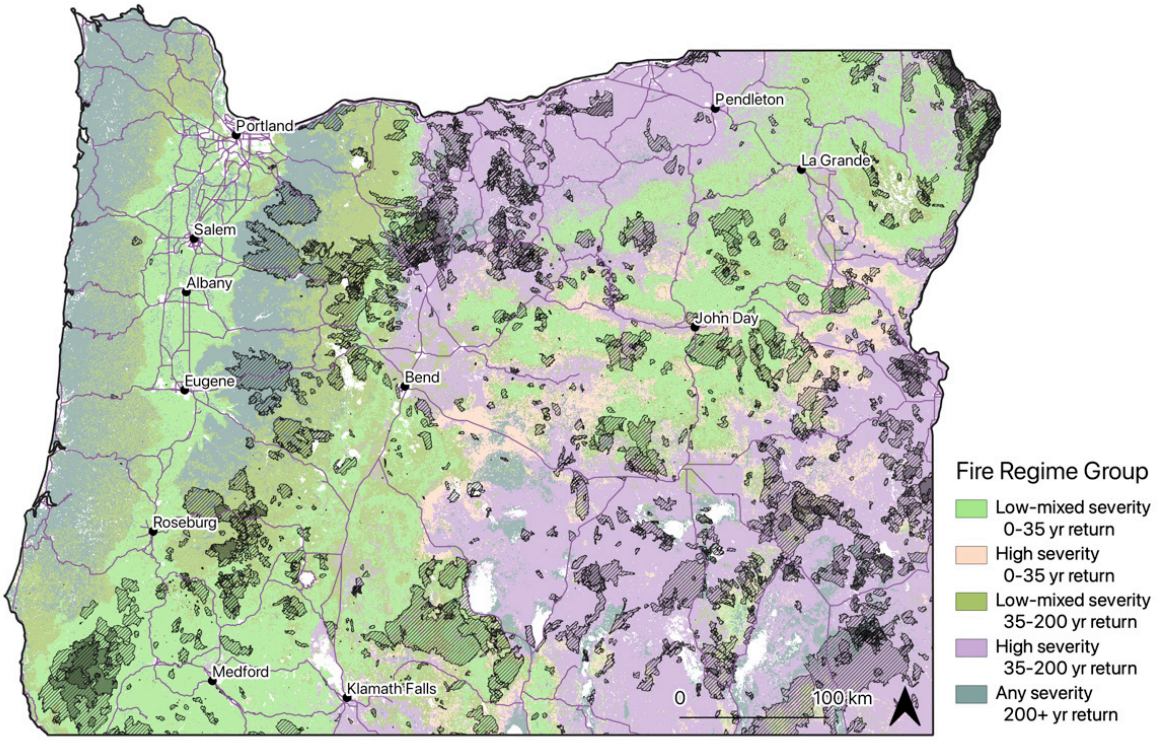

Figure 2. Total area burned in Oregon (black hatch lines) from 1984–2020 and fire regime groups. Fires smaller than 400 ha (988 acres) were omitted. Water bodies, snow peaks, and urban areas are in white. Data from Eidenshink et al. 2007 updated to 2020 (www.mtbs.gov) and LANDFIRE Remap fire regime types (landfire.gov/lf_maps.php). Figure by Cody Evers.

average annual area burned in the Clackamas Basin, an important source of water for Portland, increased by 56–540 percent from 1992–2015 to 2040–2069 under a high emissions scenario (RCP 8.5) (McEvoy et al. 2020). The projected average sizes of human-caused and lightning-caused fires on the east slope of the Cascade Range in Oregon increased by 31 percent and 22 percent, respectively, from 2006–2015 to 2031–2060, assuming a moderate emissions scenario (RCP 4.5) (Barros et al. 2021). The number of lightning-caused fires decreased by 14 percent, but the number of human-caused fires did not change (Barros et al. 2021).

In fire-prone areas of the western United States, including the mountains of Oregon, the annual number of extreme, single-day wildfire expansions was projected to increase by 100 percent if annual average temperatures increase by 2ºC (3.6˚F) above the 2002–2020 average (Coop et al. 2022). The number of wildfires in national forests in the Pacific Northwest was projected to increase by 20–140 percent from 1986–2015 to 2070–2099 under RCP 8.5 (Heidari et al. 2021). Furthermore, the area in the northwestern United States with high fire danger in summer was projected to increase by 345 percent from 1996–2004 to 2086–2094 under RCP 8.5 (Brown et al. 2021). Within Oregon, areas with the largest increases in the number of summer days with high fire danger were in the Cascade Range, Coast Range, and Klamath Mountains (Brown et al. 2021). In contrast to other projections, little change in burned area was projected over the Cascade Range and coastal mountain of Oregon and Washington (1984–2016 to 2040–2060 and 2080–2099; RCP 4.5 and 8.5) on the basis of a suite of hydrological and meteorological metrics (Brey et al. 2021). Due to increasing wildfire activity in late summer and autumn in the Pacific Northwest, $PM_{2.5}$ from wildfire smoke was projected to double under a moderate emissions scenario (SSP 2-4.5) or triple under a high emissions scenario (SSP 5-8.5) from 1997–2020 to 2080–2100 (Xie et al. 2022).

These projections of future wildfire hazard are based mainly on historical relations between a wildfire metric (e.g., size or frequency) and metrics of aridity or fire weather. However, climate change may affect the rate at which vegetation regenerates, and the plant species that become dominant, following a wildfire. For example, as the frequency of large fires increases, reduction in aboveground plant biomass (fuel loads) will eventually constrain the potential for additional large fires. Nevertheless, biomass reductions may only moderately constrain future burned area over the western United States, including dry and cold forests in Oregon east of the Cascade Range, and it is likely that biomass reduction will be lower west of the Cascade Range. The mean annual forest area burned over the next three decades may still increase by at least 50 percent compared to the previous three decades, assuming a moderate emissions trajectory (SSP 2-4.5) (Abatzoglou et al. 2021a). Uncertainties in the direction and stationarity of plant growth after fire create uncertainties in projections of wildfire-fuel feedbacks. Fuel loads may be insufficient to carry a second wildfire for 30 years after a fire in dry forests in the Intermountain West (Abatzoglou et al. 2021a). In forests in the western Cascade Range and coastal and southwestern Oregon, where plants grow more rapidly, fuel loads may constrain wildfires for shorter periods of time or may even increase wildfire frequency. For example, several short-interval megafires (e.g., Tillamook Fires, Yacolt Fires) occurred in highly productive, mesic forests in the Coast Range and western Cascade Range. Also, in the forests of southwestern Oregon, a high proportion of trees resprout and increase flammability following wildfire before the coniferous tree canopy closes (Odion et al. 2010, Tepley et al. 2017). Fire severity in Oregon's productive timber plantations is higher due to their shorter stature, spatial homogeneity, and lower bulk density (Zald and Dunn 2018, Evers et al. 2022).

In the semi-arid Big Wood River Basin in south-central Idaho, which is ecologically similar to much of south-central Oregon, the Regional Hydro-Ecologic Simulation System (RHESSYS)

model projected that increased aridity alone may reduce fuel loading by reducing productivity and increasing decomposition rates, whereas increasing carbon dioxide (CO_2) concentrations are projected to increase productivity (J. Ren et al. 2022). From about 2031–2060, the projected effects of the CO_2 increase exceeded those of the aridity increase, and both fuel loading and burned area increased under RCP 4.5 and 8.5 (J. Ren et al. 2022). By 2061–2090, the projected effects of the aridity increase exceeded those of the CO_2 increase under RCP 8.5, and burned area decreased.

Climate change-mediated shifts to larger, more severe, and more frequent wildfires may also affect tree species composition and vegetation structure in the relatively cool, moist Cascade Range (Enright et al. 2015, Halofsky et al. 2020). For instance, in some upper-montane and subalpine forests, few wildfires occurred or were suppressed during the past several hundred years. In these areas, assuming seeds are available, frequent fires and drier and warmer postfire growing seasons may lead a transition to patchy, low-density, conifer-dominated forests that are better adapted to warmer and drier conditions (Busby et al. 2020, Busby and Holz 2022).

COVID-19 and Wildfire

Restrictions and shutdowns in response to the COVID-19 pandemic caused a reduction in emissions from industry, transportation, and other activities. The sudden decrease in fine particulate matter (aerosols) in the atmosphere during the pandemic may have led to an increase in air temperature and a reduction in precipitation and relative humidity from August through November 2020, and therefore made conditions more favorable for wildfire (L. Ren et al. 2022). The strongest modeled effect was in the southwestern United States, whereas the effect in Oregon was small.

The pandemic may also have changed the incidence of human-caused ignitions. Fewer active wildfires in the southeastern United States were reported following shutdowns beginning in March 2020, although the decrease largely was attributed to the cancellation of prescribed burns used to manage wildfire hazard (Poulter et al. 2021). Unintentional wildfire ignitions, however, may also have been affected. Visits to state and national parks across the northwestern United States were positively correlated with county-level COVID-19 case numbers before the peak 2020 wildfire season, suggesting people looked to parks for temporary relief from restrictions on other common social activities (Yang et al. 2021). More park visitors, and possibly a larger proportion of visitors with little outdoor experience, could have led to a greater number of unextinguished or unattended campfires, and therefore a higher probability of wildfire, although any connection is still speculative.

Because the fine particulate matter in wildfire smoke can adversely affect the human respiratory system, it is likely that the 2020 wildfires in the western United States contributed to the adverse health effects of COVID-19 (Zhou et al. 2021). In 18 of 19 Oregon counties analyzed, the number of reported COVID cases increased on days on which concentrations of $PM_{2.5}$ exceeded 21 $\mu g\ m^{-3}$ (Zhou et al. 2021).

There is general agreement that wildfire hazard in the western United States has increased over the last few decades and will continue to increase over the next several decades. The average annual area burned in Oregon's forests is expected to increase by at least 50 percent, and fire seasons are expected to become more extreme than any in recorded history. The risk to human life and property is considerable, particularly in western Oregon where communities have little historical experience with major wildfires (Dye et al. 2021, McEvoy et al. 2021). Past, present, and future land use will also affect wildfire hazard during the coming decades (Hanan et al. 2021, Prichard et al. 2021).

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Lightning-Caused Wildfires

Dmitri Kalashnikov

Lightning in Oregon is most frequent over the high terrain east of the Cascade Range, and relatively rare west of the Cascade Range (Figure 1a). The density of lightning is particularly high over mountain ranges that intersect with monsoonal flow from the south during summer, including the Wallowa Mountains, Blue Mountains, and portions of the central and southern Cascade Range (Figure 1a). The annual number of cloud-to-ground lightning flashes peaks in nearly all locations east of the Cascade Range, and many locations in Oregon's southwestern interior valleys, during June, July, and August (Figure 1b) (Kalashnikov et al. 2020).

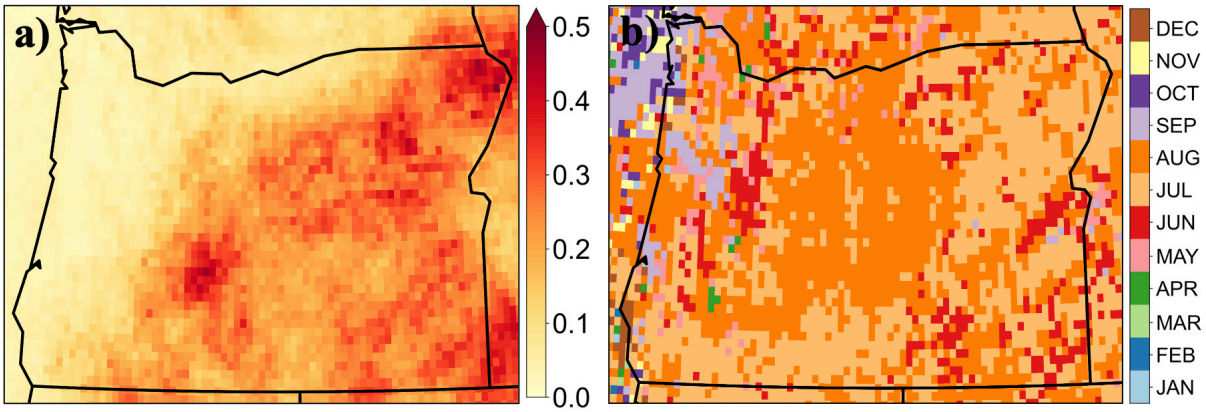

Figure 1. Mean annual cloud-to-ground lightning density (flashes/km^2/year) (a) and peak month of cloud-to-ground lightning activity from 1988–2017 (b). Lightning data are from the National Lightning Detection Network. Figures adapted from Kalashnikov et al. 2020.

Although some summer thunderstorms produce heavy rain and flash flooding (Smith et al. 2018), in other situations rainfall passes through a dry layer of the atmosphere and evaporates before reaching the ground. Lightning that strikes the ground without substantial rainfall at the surface is known as dry lightning (Rorig and Ferguson 1999, Abatzoglou et al. 2016). When rainfall accompanies lightning, any fires sparked by lightning are more likely to be extinguished, which does not happen in situations with dry lightning.

Dry lightning is a major cause of wildfire ignitions east of the Cascade Range during summer, when live and dead vegetation is dry (Rorig and Ferguson 1999, Abatzoglou et al. 2016, Balch et al. 2017). Lightning-caused ignitions outnumber those caused by human activity in central and eastern Oregon (Figure 2a), with most fires due to lightning occurring from May through September (Figure 2b). The likelihood of large, lightning-caused fires is especially acute during drought years, as wildfire burned area is more strongly correlated with climatic conditions than with the density of lightning flashes (Barbero et al. 2014, Abatzoglou et al. 2016, Brey et al. 2021). During the summers of 2020 and 2021, drought across large parts of Oregon east of the Cascade Range was moderate to severe, leaving vegetation more flammable than normal (Higuera and Abatzoglou 2021). As a result of conducive weather and climate conditions, some lightning-caused wildfires (Figure 3), including the Lionshead Fire, which started on the Confederated Tribes of Warm Springs Reservation (205,000 acres [83,000 ha] burned in 2020), and the Bootleg Fire, which started in Klamath County (414,000 acres [167,000 ha] burned in 2021), grew into megafires that burned for several weeks, destroyed

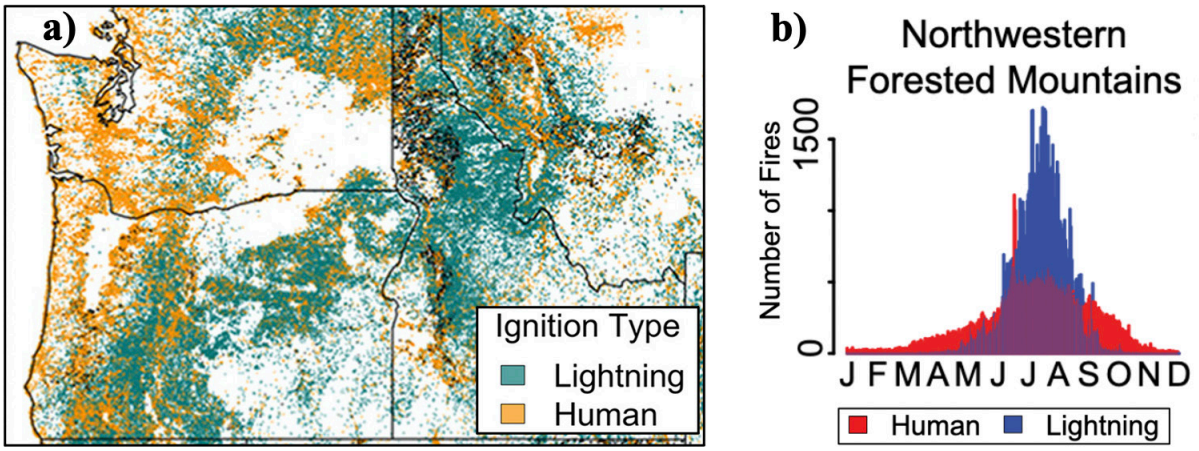

Figure 2. (a) Location and ignition type of wildfires from the federal Fire Program Analysis Fire Occurrence Data (1992–2015) from Brey et al. 2018. Reprinted with permission from John Wiley and Sons. (b) Seasonal distribution of human and lightning-caused wildfires over the Northwestern Forested Mountains ecoregion (1992–2012) from Balch et al. 2017. Reprinted with permission from the journal.

many homes, and exposed communities to high concentrations of smoke, which is associated with numerous public health impacts (see *Public Health*, this volume).

Lightning, and lightning-caused wildfires, are an inherent part of Oregon's climate and ecology east of the Cascade Range (Agee 1993). Nevertheless, human-caused climate change has the potential to increase the number, severity, and size of wildfires. Across Oregon, the number of wildfires ignited by lightning has increased in the past three decades (Dalton and Fleishman 2021). A warming, drying climate has similarly caused increases in the area burned by wildfires across the western United States in recent decades, irrespective of ignition source (Abatzoglou and Williams 2016, Holden et al. 2018). Trends in lightning are more difficult to ascertain due to inconsistencies in the observing network over time (Cummins and Murphy 2009), and future projections of lightning for Oregon also are uncertain (Villarini and Smith 2013, Hoogewind et al. 2017). However, the area burned by lightning-caused fires in central Oregon (Barros et al. 2021) and the western United States (Li et al. 2020) is projected to increase during the twenty-first century due to anticipated further warming and drying of the region during summer.

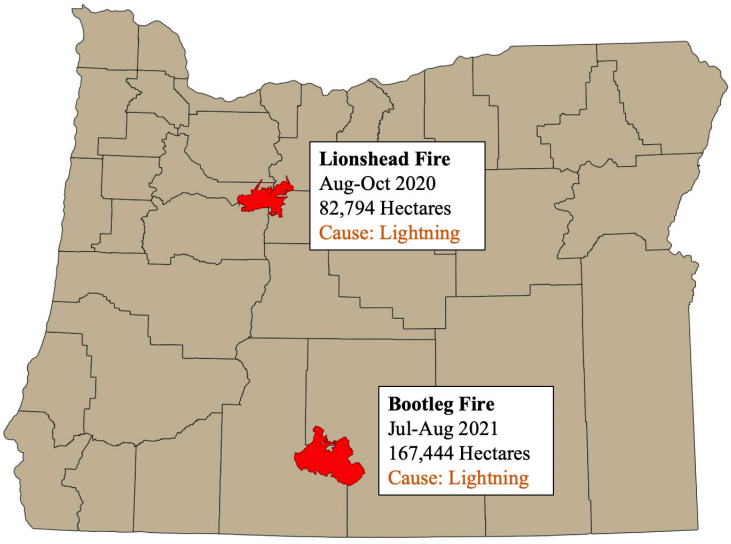

Figure 3. The Lionshead and Bootleg Fires. Wildfire perimeters and burned area from the National Interagency Fire Center (2022).

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Wildfires, Behaviors, and Policy Support

Hilary Boudet, Leanne Giordono, Muhammad Usman Amin Siddiqi, Greg Stelmach, Chad Zanocco, and June Flora

Extensive wildfires in September 2020 (see *Wildfire Trends and Drivers*, this volume) shaped Oregonians' disaster preparedness and support for climate mitigation and adaptation policies. From 28 December, 2020, through 23 February, 2021, we administered a survey to a sample of 1308 Oregonians whose distribution of gender, age, and education mirrored that of the general Oregon population. We asked survey recipients about their experience with the wildfires, their attitudes and beliefs about the link between the wildfires and climate change, their behaviors related to personal and property protection, and their support for policies designed to reduce the risk from future wildfires (Boudet et al. 2021, 2022; Giordono et al. 2021).

Factors Associated with Disaster Preparedness and Community Helping Actions

We examined and compared factors associated with two types of individual-level behaviors, disaster preparedness and community helping (volunteering and donations), after the wildfires (Siddiqi et al. unpublished ms). Disaster preparedness can mitigate risks associated with future wildfires, whereas volunteering and donations can add surge capacity that aids trained emergency personnel in responding to more-frequent disasters in the future.

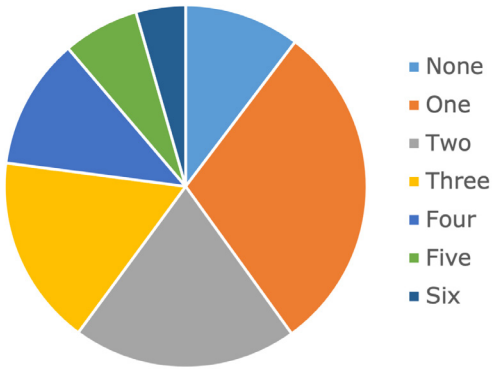

Figure 1. Number of personal actions taken to prepare for future wildfires.

Ninety percent of our survey respondents reported engaging in at least one personal action to prepare for future events (Figure 1). Common actions ranged from evacuation planning to mitigating health threats to vegetation management (Figure 2). Forty-four percent of respondents reported either donating to or volunteering with a group responding to the 2020 wildfires. Those who reported a higher number of disaster preparedness actions also were more likely to report community helping behavior. For example, 15 percent of those who took no action, 33 percent of those who took one action, and 69 percent of those who took five actions reported such helping behavior.

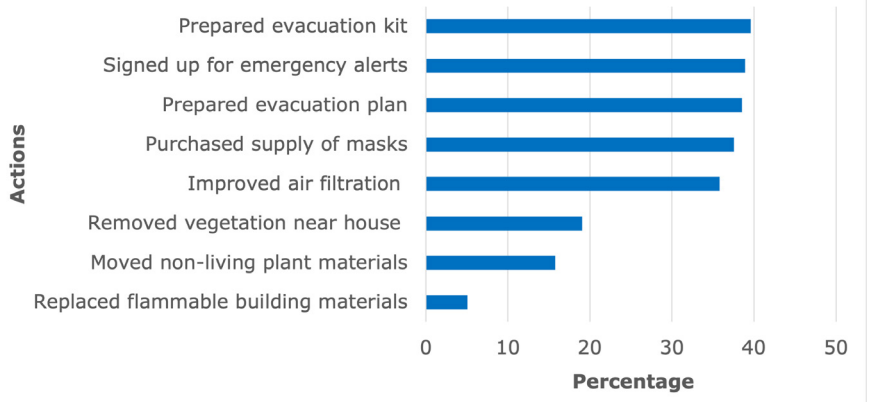

Figure 2. Types of actions taken to prepare for future wildfires.

We conducted multivariate analyses to assess the effects of social and demographic variables, beliefs, event-related harm, social interactions, descriptive norms, and information sources on disaster preparedness (ordinal logistic regression) and community helping behaviors (logistic

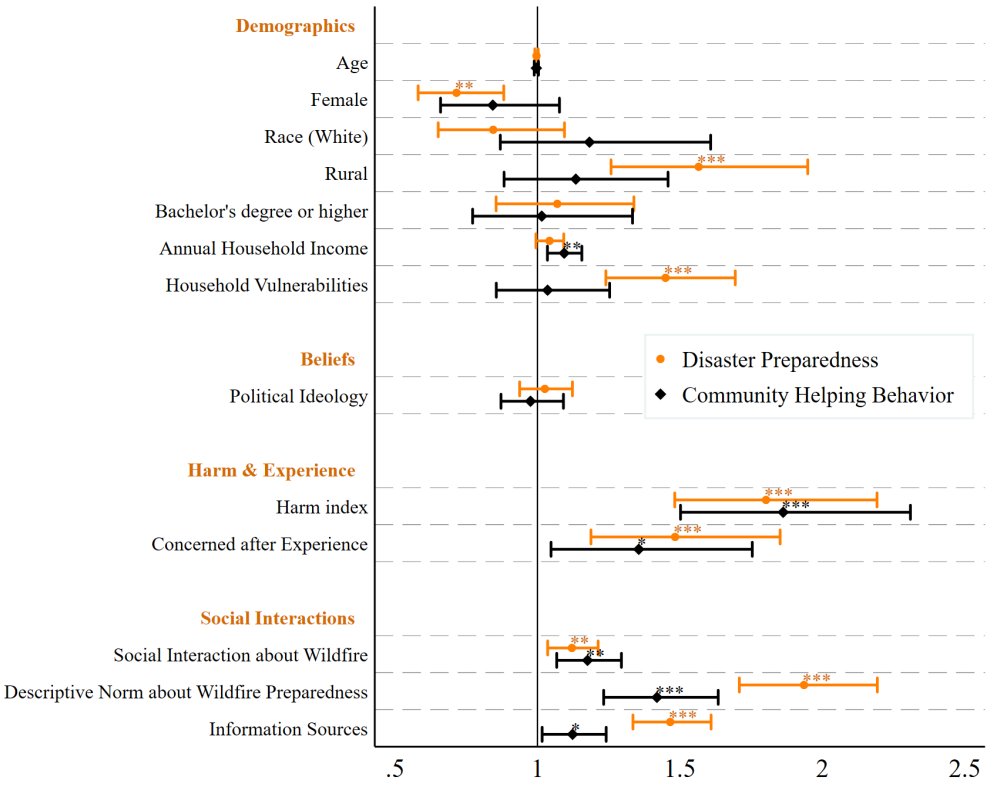

Figure 3. Factors associated with disaster preparedness (number of actions taken to prepare for future wildfires) and community helping behavior (donating or volunteering at least once). Estimates and 95% confidence intervals (capped lines) that did not overlap 1.0 were considered to be statistically significant (*, p <0.05; **, p <0.01; ***, p <0.001).

regression). Male respondents, those living in rural areas, and those who had vulnerable individuals in their households were significantly more likely to report that they took a greater number of actions to prepare for future wildfires (Figure 3). People from higher-income households were more likely to report that they donated or volunteered. Age, race, educational attainment, and political ideology were not significantly associated with disaster preparedness and community helping actions (Figure 3).

Reported harm from the 2020 Oregon wildfires and social and media interactions were also linked to disaster preparedness and community helping actions. We developed a composite mean index of reported harms from the fires to daily activities, property, finances, physical health, and mental health. Those who reported experiencing a higher degree of harm from the wildfires reported taking a greater number of disaster preparedness actions, and they were more likely to report a community helping action (Figure 3). We also developed a second experience-related variable, whether a respondent reported being more concerned about climate change after their experience with the wildfires. Although neither disaster preparedness nor community helping actions were associated with respondents' political ideology, those who reported more concern about climate change after experiencing the 2020 wildfires were more likely to report preparedness and community helping actions (Figure 3).

Our findings were consistent with earlier research on the role of information sources, wildfire-specific social interactions, and subjective norms in shaping behavioral intentions and outcomes. Respondents who sought information about the wildfires from more sources (e.g., television news, local newspapers, online sources); talked more frequently with friends and family about the wildfires; and thought that higher percentages of their friends, neighbors, and community members were taking actions to prepare for future wildfires were more likely to report preparedness and

community helping actions. These results suggested that information seeking, communication, and experience affect individual actions after wildfires.

Drivers of Support for Climate Policies

Among our respondents, 59–89 percent reported strong support for policies designed to mitigate carbon emissions (Figure 4), and 50–93 percent reported strong support for adaptation policies designed to limit the impacts of future extreme events (Figure 5).

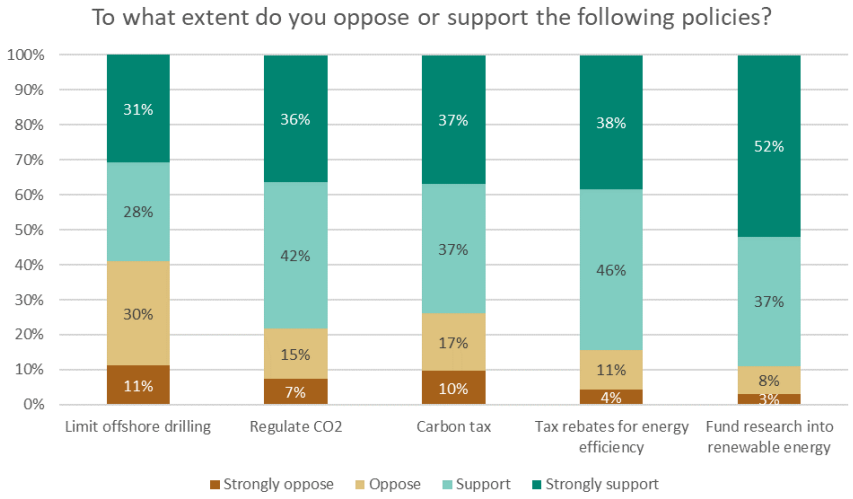

Figure 4. Public support for climate mitigation policies.

We used ordinary least squares models to estimate associations between key factors (e.g., social and demographic factors, event experience, event attribution beliefs, risk perceptions, information processing) and policy support. Our dependent variables included five adaptation policies and an index of mitigation policies. We then used seemingly unrelated estimation to formally assess similarities and differences between drivers of support for mitigation and adaptation policies (Figure 6).

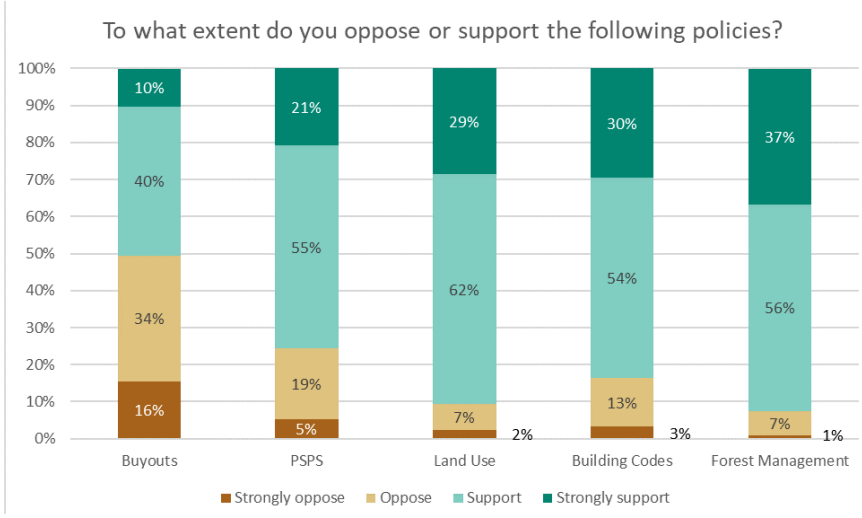

Figure 5. Public support for climate adaptation policies.

Common drivers of support for both mitigation and adaptation policies included political ideology, perceived causes of the wildfires, and climate change concern. Conservatives expressed less support for both types of climate policies than liberals, whereas more support was expressed by individuals who attributed the wildfires primarily to climate change and those who reported more concern about climate change after experiencing the 2020 wildfires. However, the effects differed in magnitude. Political ideology was more strongly associated with support for mitigation policies than for adaptation policies, whereas causal attribution and climate change concern were more strongly associated with adaptation-policy support. Our results suggest that attitudes toward adaptation policies may be less politicized than attitudes toward mitigation policies.

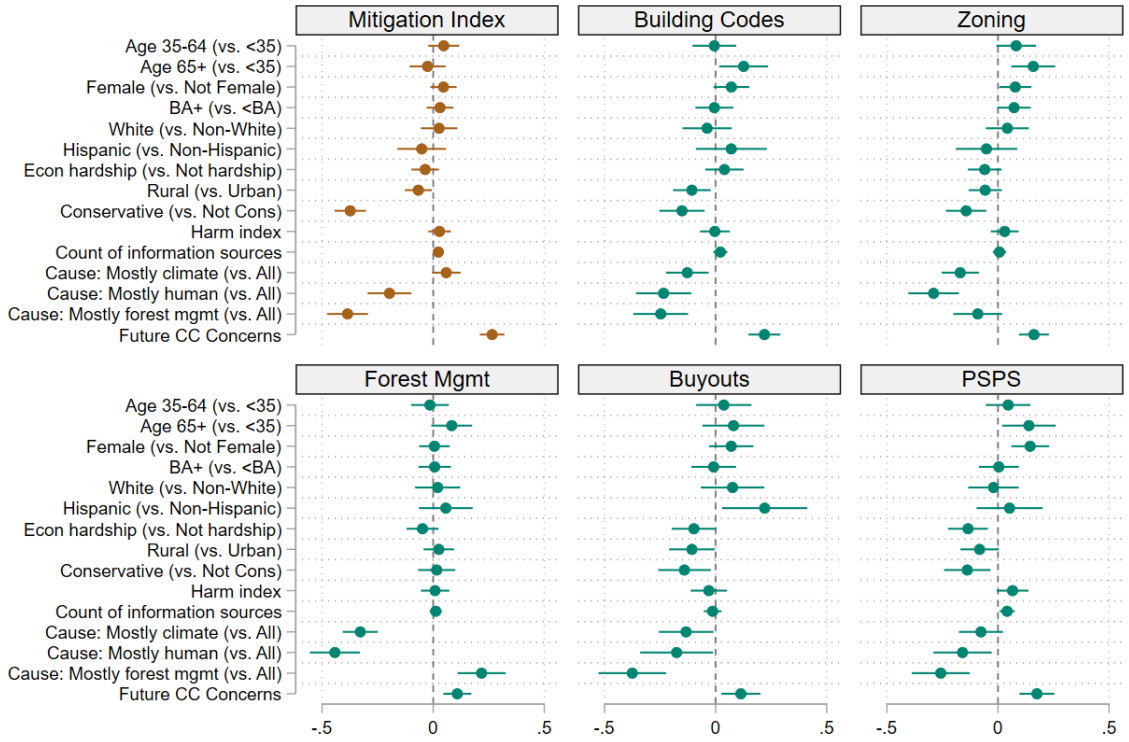

Figure 6. Factors associated with support for mitigation and adaptation policies. PSPS, public safety power shutoffs. Estimates (circles) and 95% confidence intervals (lines) that do not overlap 0 were interpreted as evidence of strong associations.

We also found evidence of associations between demographic characteristics and policy support. Respondents living in rural areas, compared to those in more urban settings, expressed less support for mitigation policies and selected adaptation policies—especially stricter building codes, property buyouts, and public safety power shutoffs (when utility companies shut off electricity to limit wildfire risk). These results may reflect the locally accrued costs of such adaptation policies, which are likely to place more burden on rural residents, especially homeowners, than on urban residents. Although there was no association between age and support for mitigation policies, there was a positive association between age and support for selected adaptation policies, including building codes, land use, and public safety power shutoffs.

Furthermore, the survey responses indicated a link between respondents' exposure to poor air quality during the wildfires and support for public safety power shutoffs (Zanocco et al. 2022). Not only did a strong majority support public safety power shutoffs as an adaptation strategy (Figure 5), but exposure to higher concentrations of wildfire smoke was correlated with higher levels of support. We used U.S. Environmental Protection Agency monitoring station data to estimate daily average air quality index (AQI) values for each respondent's zip code during September 2020. Survey respondents who experienced the worst air quality during that month, as measured by the maximum AQI and the number of days on which air quality was unhealthy, were more likely to support public safety power shutoffs than those who lived in areas with better air quality.

Although public safety power shutoffs are only one among many means of reducing wildfire risk, high levels of support for the shutoffs, especially among those who were exposed to wildfire smoke, suggest that Oregonians may be receptive to shutoffs. An important caveat, however, is

that public safety power shutoffs have not been widely deployed as a mitigation strategy in Oregon, and widespread implementation may reduce support. Additionally, at least in the near term, the effects of public safety power shutoffs are unlikely to be equitable. Sustained power outages can pose substantial health risks, especially to vulnerable populations, due to loss of home cooling and medical equipment. Public safety power shutoffs are most likely to occur in rural areas, which often lack public resources to offset such losses for those who do not have financial resources to secure backup power sources such as gasoline-powered generators or solar-plus-storage battery systems.

There was an equally strong and consistently positive association between concerns about future risks from climate change and support for mitigation and adaptation policies. Our results suggest that concerns about the climate change-driven risks of similar future events surpass, or potentially supplant, the effects of harms experienced during the event in shaping policy support.

Individuals who attributed the wildfires primarily to climate change tended to express consistently less support for adaptation policies than those who attributed the wildfires to a more-diverse set of causes. This suggests a reluctance among individuals who attributed the wildfires almost solely to climate change to shift from mitigation-oriented solutions to adaptation-oriented solutions. It is possible that a strong social identity (for example, as a climate-change fighter) may preclude alternative actions. In contrast, those who attributed the wildfires to forest management practices tended to be less supportive of mitigation policy and more supportive of changes in management.

Our results suggest that Oregonians took personal and community helping actions in the wake of the wildfires to better protect themselves from future events and to help their communities recover. The results also suggest relative high levels of support for climate policies designed to limit emissions (mitigation) and the impacts of future extreme events (adaptation). Nevertheless, people took different pathways to these actions and support. Policy support, especially for or against mitigation policy, appeared more strongly related to political ideology, whereas personal preparedness and community helping actions were more strongly tied to information seeking, social interactions, perceived norms, and event experience.

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Public Response to the 2020 Wildfire Smoke Event in Oregon

Michael Coughlan, Heidi Huber-Stearns, Benjamin Clark, and Alison Deak

Introduction

In September 2020, smoke from multiple large wildfires covered much of the west coast of the United States, causing an unprecedented decline in air quality for consecutive days. During this period, the Oregon Department of Environmental Quality (DEQ) observed record-high levels of hazardous air pollution in six of Oregon's major population centers (Figure 1). Air quality in some communities in Oregon was so hazardous that it exceeded the maximum value, 500, on the U.S. Environmental Protection Agency's air quality index (AQI). Air quality in Eugene, Oregon, was hazardous (AQI 301–500) for eight consecutive days. Although this event was unusually severe and occurred over an extraordinary large area and time period, the frequency and severity of wildfire smoke events in Oregon has increased over the past decade and is projected to increase further (Yang et al. 2022).

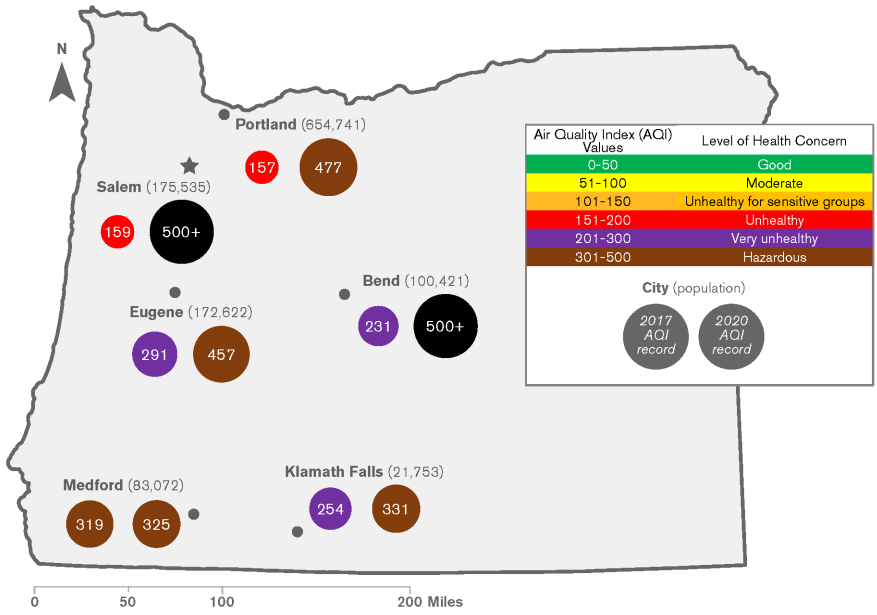

Figure 1. Air Quality Index (daily $PM_{2.5}$ and other health-related pollutants) records set in 2017 (left circle) and 2020 (right circle) in Oregon's six largest population centers.

Public attitudes, knowledge, and behavioral responses to wildfire smoke are not well studied, in part because wildfire-related research has primarily focused on responses to the fires (e.g., suppression, mitigation, evacuation, recovery) rather than the hazards of smoke. Yet wildfire smoke is a serious concern for public health because it is a substantial source of aerosols (particulate matter <2.5 microns in diameter, or $PM_{2.5}$) and other air pollutants (Wiedinmyer et al. 2006, Yu et al. 2022). High $PM_{2.5}$ levels (>150 AQI) can yield adverse respiratory outcomes, particularly asthma and chronic obstructive pulmonary disease, increased heart disease, and cardiac arrest (Dixon and Robertson 2018; also see *Public Health*, this volume). Exposure to wildfire smoke is the most common way that people experience wildfires (Navarro et al. 2018). It is becoming increasingly clear that smoke from wildfires poses an order of magnitude greater threat, in terms of deaths and total costs to society, than wildfire flames themselves (Doerr and Santín 2016; also see *The Economic Implications of Climate Change for Oregon*, this volume). Although U.S. air quality improved in recent decades due to the regulation of transportation and industrial pollution, an increase in the number and size of wildfires in the western United States has contributed to declining air quality through the associated smoke (McClure and Jaffe 2018, O'Dell et al. 2019, Yu et al. 2022).

Climate change is a major driver of increases in wildfire occurrence, severity, and wildfire smoke exposure in the western United States (Westerling et al. 2006, Westerling 2016, Iglesias et al. 2022). Given current climate trends, wildfire smoke hazards will likely continue to grow in this region (Wiedinmyer et al. 2006, Liu et al. 2016, Yang et al. 2022). The challenge is not only learning how to live with the increased frequency and severity of wildfires but learning how to respond to smoke. Here, we present the results of a state-wide survey, conducted in summer 2021, that asked respondents about their experiences with smoke and air quality during the 2020 wildfires. Given the widespread acknowledgment of the magnitude of smoke, its duration, and the number of communities and individuals exposed during those events, it will be highly informative and useful to track changes in public knowledge, attitudes, and behaviors surrounding smoke in the future. We suggest that our survey can serve as a baseline reference for future assessments of Oregon residents' concerns and responses to wildfire smoke.

Methods

We designed a social survey instrument to collect data on Oregon residents' concerns, communication needs, and responses to wildfire smoke during the 2020 wildfire season. We administered the survey electronically via the Qualtrics software application for data collection. Respondents could take the survey in either English or Spanish. To maximize data collection efficiencies and retain respondent attention by minimizing total response time, many of the survey questions allowed for multiple response options and used display logic tied to the previous responses. The survey instrument is available from the University of Oregon Scholars' Bank (scholarsbank.uoregon.edu/xmlui/handle/1794/26984).

We distributed the survey through two recruitment efforts that we refer to as recruitment A and recruitment B. Recruitment A relied on an internet audience panel, and provided participants with a hyperlink to the Qualtrics survey. Although the goal of recruitment A was to obtain a representative sample, rural populations were oversampled to provide a more-even distribution of urban and rural perspectives and experiences. Recruitment B was designed to draw a targeted sample of Oregon residents who identify as Hispanic or Latinx to better understand one of Oregon's largest historically under-represented groups. Sampling for recruitment B relied on a Facebook marketing campaign, provided a monetary incentive (gift card), and targeted Oregon residents who speak Spanish or identify as Hispanic or Latinx. The two recruitment methods have distinct potential sampling biases. Different assumptions and considerations are necessary to understand how the resulting samples relate to the whole population. Given these issues, we conducted separate statistical analyses for each recruitment and describe many of the responses with respect to each sample.

We hypothesized that past experiences with smoke, urban or rural residency, housing situations, language preferences, ethnicity, physical ability, and other demographic factors that make people more or less vulnerable to smoke impacts would influence their communication preferences and how they experienced wildfire smoke during the 2020 wildfire season. Consequently, in addition to asking respondents for standard demographic information, we collected data about where they live, how often they are exposed to smoke, and characteristics of their household. We used these data to construct explanatory factors for statistical analysis (Table 1). For example, respondents with rural zip codes were coded as members of the rural demographic explanatory factor (rural = 1), and those with urban zip codes were coded as not belonging to the rural demographic (rural = 0). Similarly, we asked respondents to report their age by categories: 18–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, and 85 or older. Respondents who selected age categories of 65 years or older

were coded as older respondents (older = 1), and those who selected age categories as under 65 years of age were coded as not older (older = 0).

Explanatory factor groups	Type of factor	Definition	Recruitment
Rural	Geographic	Respondent zip code	A&B
Older	Age	Respondents 65 years of age or older	A
Lower income	Household income	Respondents who reported that their household rarely or sometimes has enough money to pay bills	A&B
Disability	Abilities	Respondents who reported living with one or more disability	A&B
Non-homeowner	Housing	Respondents who did not own a home	A&B
Non-English language	Language preference	Respondents who reported a preference for a language other than English	A
Spanish	Language preference	Respondents who reported a preference for Spanish	B
Hispanic/Latinx	Ethnicity	Respondents who self-identified as Hispanic or Latinx	A
Non-white or Hispanic/Latinx	Ethnicity	Respondents who self-identified as an ethnicity other than White, Hispanic, or Latinx	A
High exposure	Smoke exposure	Respondents who reported more than five days of exposure to smoke per year	A&B
Vulnerable populations	Multiple	Respondents who either met the U.S. Environmental Protection Agency criteria for populations more vulnerable to smoke or who reported that one or more members of their household fit those criteria[1].	A

[1]Vulnerable populations are considered to be at higher risk of health impacts from wildfire smoke. These groups include people with asthma, other respiratory diseases, or cardiovascular disease, children, pregnant women, adults 65 years of age or older, people of low socioeconomic status, and outdoor workers (U.S. EPA 2021).

Table 1. Demographic explanatory factor groups, definition, and applicability to recruitment groups.

Due to sampling criteria and limitations, some factors were only applicable for analysis of one of the recruitment groups. For example, we could not assess statistical relationships for the older demographic factor for recruitment B because no respondents in that sample were 65 or older. Similarly, we did not assess the Hispanic/Latinx demographic factor for recruitment B because that group comprised 100 percent of the sample. By contrast, we did not assess Spanish language preference in recruitment A because too few respondents indicated a preference for Spanish.

Because multiple response options were possible for many of the questions, we used logistic regression to assess whether relationships between a response option and membership or non-membership in an explanatory demographic were statistically significant ($p < 0.05$). Below, we report odds ratios and p-values for a selection of our statistically significant results. Odds ratios are measures of association between an explanatory factor (in our case, membership in a particular demographic group) and an outcome (selection of a given response). In our analysis, odds ratios indicate the probability that a response was selected relative to the probability that it was not selected, given membership or non-membership in each of the set of demographic criteria (Table 1). Data, including the coding used in the logistic analysis, are available from the University of Oregon Scholars' Bank (scholarsbank.uoregon.edu/xmlui/handle/1794/27175).

Results

We obtained 1200 responses from Oregon residents who experienced the 2020 wildfire smoke events, 971 from recruitment A and 229 from recruitment B. Responses were split between rural and

urban zip codes. Fifty percent of respondents in recruitment A, and 23 percent in recruitment B, were rural (45 percent rural total) (Figure 2). Full demographic details are archived at scholarsbank.uoregon.edu/xmlui/handle/1794/27179. Approximately 85 percent of recruitment A respondents identified as White, compared with 87 percent of Oregon residents (Figure 3) (www.census.gov/quickfacts/OR). The 6 percent of respondents who identified as Hispanic or Latinx represented the largest non-White identity. By contrast, 13 percent of Oregon residents identify as Hispanic or Latinx. However, across the two recruitments, 24 percent of respondents identified as Hispanic or Latinx. Across the two recruitments, 91 percent of respondents selected English as their

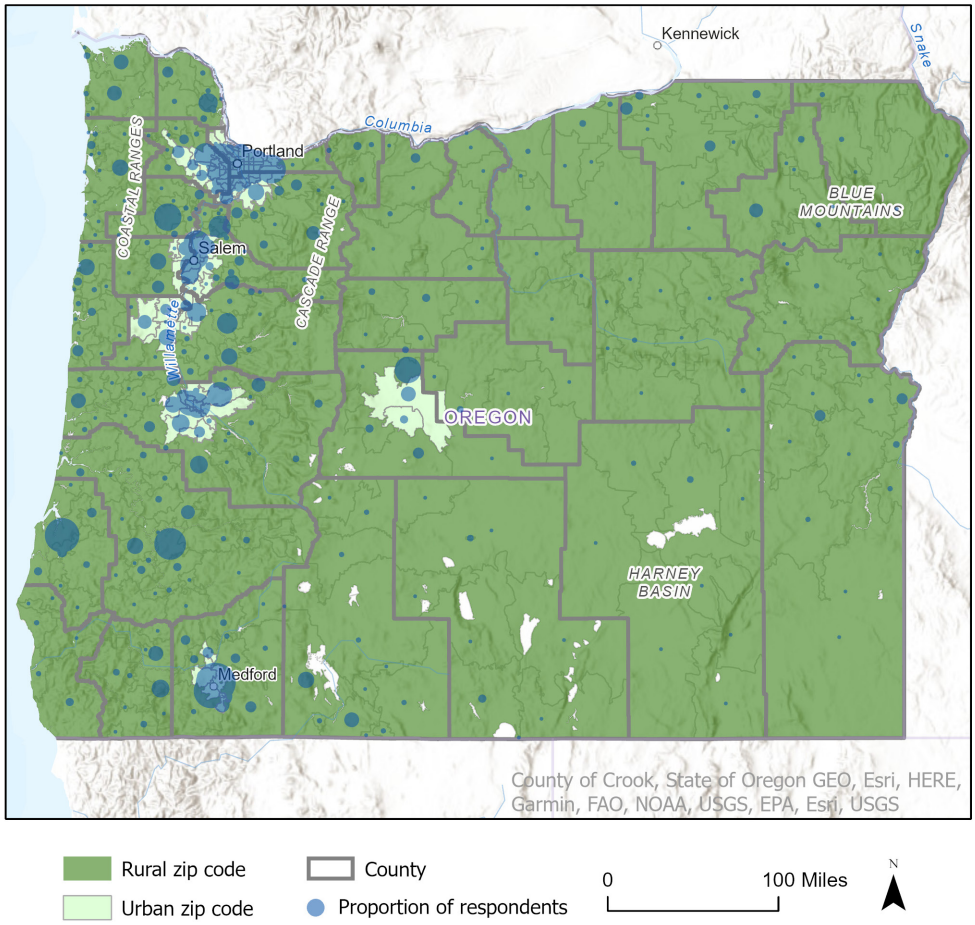

Figure 2. Urban and rural zip codes, counties, and the proportion of respondents from each zip code. The proportion of respondents is represented by blue circles centered on the zip code geography.

preferred spoken language (Figure 3). Another 7 percent selected Spanish, followed by Vietnamese (n=4), Russian (n=2), Mandarin (n=2), Cantonese (n=2), and simplified and Chinese (n=1). Ten respondents selected "other" as a preferred language; text entry included two Japanese and one each Norwegian, German, and Korean. Respondents' ages were fairly evenly distributed across age categories, but with lower representation of populations 75 years old or older; no individuals over 55 were represented in recruitment B. For gender identity, 49.5 percent selected "woman", 47.5 percent "man", 2 percent "non-binary/non-conforming", 0.5 percent "prefer to self-identify", and 0.5 percent "prefer not to answer." Approximately 45 percent of respondents reported having at least

one disability, with physical disabilities (16 percent) and mental health disabilities (15 percent) the most common.

We identified 99 positive and 85 negative statistically significant associations (of 688 possible) between a given explanatory factor and question response (Table 2; respondents could select multiple responses for many questions). Below we highlight several of the more relevant results.

Vulnerable Populations Within Respondent Households

Respondents' demographics and responses to a question about the potential vulnerability of respondents' household members suggested that one or more members of the households of 85 percent of respondents, including themselves, are potentially more vulnerable to harm from wildfire smoke. In total, 36 percent of respondents met one or more criteria for increased vulnerability to wildfire smoke impacts, whereas another 49 percent responded that at least one of their household members met those criteria. For some groups, this percentage was even higher. For example, 86 percent of respondents from recruitment A who identified as Hispanic or Latinx reported that their household included members of vulnerable populations. By comparison, nearly 100 percent of recruitment B respondents reported household members who could be considered more vulnerable. Across the two recruitment efforts, 97 percent of Hispanic/Latinx respondents and 83 percent of rural respondents reported that at least one member of their household could be considered more vulnerable to wildfire smoke.

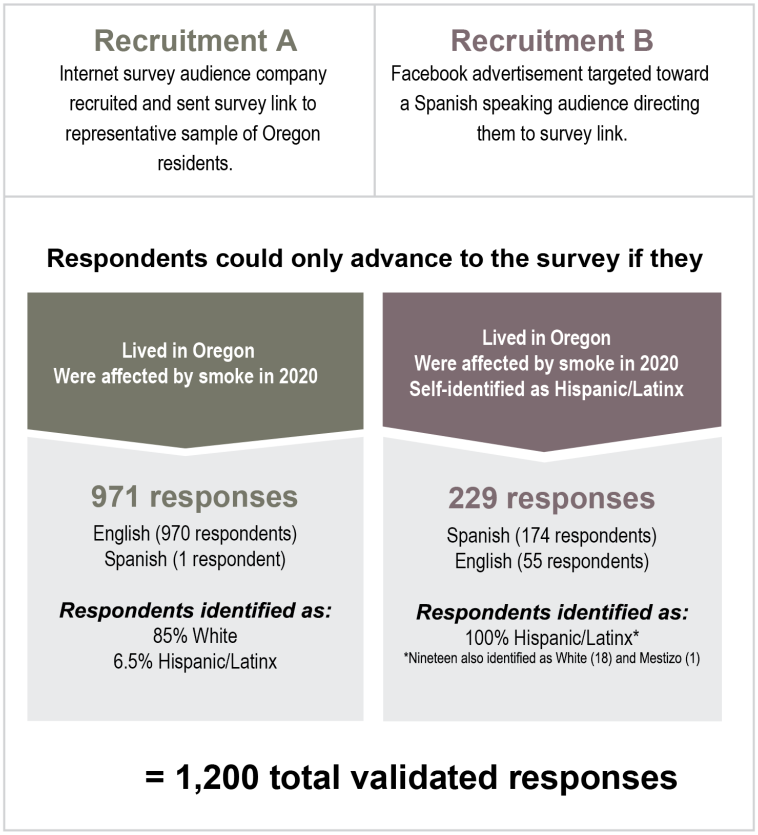

Figure 3. Survey response results for the two recruitment efforts.

Smoke Exposure

We asked respondents how often they think they are exposed to unhealthy air quality from wildfire smoke in a given year (Figure 4). Across the two recruitment efforts, 38 percent of respondents reported perceived exposure on five or more days per year. Twenty-three percent of rural residents, and 16 percent of all residents, reported perceived exposure over more than two weeks per year.

Evacuations

We asked respondents if they evacuated to a different location because of smoke or wildfire in 2020. Over 25 percent reported that they evacuated. The percentage of evacuees in recruitment B

Table 2. Associations between recruitment-specific explanatory factors and question responses. Odds ratios <1.0 and >1.0 indicate negative and positive associations, respectively (respondents within the specified group were less likely or more likely than not, respectively, to select the response). Negative associations are shaded gray.

Question	Response	Recruitment	Explanatory factor	Odds ratio	P-value
Q3.2 Did you have any concerns about air quality during the 2020 wildfire season?	I was concerned about the risks of smoke to my health	A	Rural	0.61	0.001
		A	Exposed	1.91	0.000
Q3.7 Which of these factors contributed the most to your preparedness?	I have experienced smoke events before	A	Rural	1.58	0.035
		A	Exposed	1.66	0.020
Q3.8 Would you have felt more prepared if you had access to . . .	Clean air shelters in my community	A	Low income	1.88	0.004
		A	Vulnerable household	1.66	0.023
		A	Do not own home	1.54	0.018
Q3.9 Did you take any protective measures or make changes to your routine outdoor activities?	Yes	A	Low income	0.67	0.047
		A	Do not own home	0.65	0.005
		B	Low income	0.22	0.032
		A	Vulnerable household	1.55	0.011
		A	Exposed	1.41	0.029
Q3.10 Which of the following protective actions for outdoor air did you take?	Stay home or reduce the number of times I left my home	A	Low income	0.67	0.041
		B	Exposed	0.38	0.017
	Avoid or reduce the total time I spent in usual outdoor recreation or exercise	A	Do not own home	0.58	0.000
		A	Rural	0.75	0.035
	Use a N95, KN95, or respirator when outdoors	A	Rural	0.53	0.000
		A	Vulnerable household	1.77	0.013
		B	Exposed	3.49	0.004
	Use another type of mask outdoors	A	Exposed	1.40	0.039
Q3.11 Did you take any protective measures while indoors?	Yes	A	Low income	0.64	0.027
Q3.12 Which of the following protective actions did you take while indoors?	Installed or used HEPA air purifiers	A	Rural	0.67	0.028
		A	Vulnerable household	1.25	0.335
	Installed or used a homemade box fan HEPA air filter indoors	A	Vulnerable household	2.18	0.023
	Installed or used a commercial HEPA or HVAC air system	A	Exposed	2.44	0.008
	Created a cleaner air space in my home (e.g., kept windows and doors shut)	B	Exposed	2.71	0.029
		B	Do not own home	0.28	0.001
		B	Low income	0.25	0.002
	Used a N95, KN95, or respirator when indoors	B	Disability	13.91	0.000
		B	Exposed	4.95	0.000

Question	Response	Recruitment	Explanatory factor	Odds ratio	P-value
Q3.5 What information about smoke-related air quality would you like to have? (Select all that apply)	How to stay safe while engaging in outdoor activities	A	Exposed	1.50	0.004
		B	Exposed	4.71	0.000
	Information about personal protective equipment	A	Exposed	1.78	0.000
		B	Prefer Spanish	3.11	0.004
		B	Disability	3.75	0.001
	Forecasts about air and smoke conditions	A	Exposed	1.93	0.000
		B	Prefer Spanish	4.49	0.001
		B	Disability	6.30	0.000
	Safety of food from my garden or the market	B	Prefer Spanish	3.29	0.007
	How to stay safe while indoors	B	Disability	4.29	0.000

(76 percent) was considerably higher than that in recruitment A. Although this result should not be interpreted as representative of the entire Hispanic/Latinx population in Oregon due to the methods used for recruitment, it is notable.

Concerns About Smoke During the 2020 Wildfire Season

Approximately 72 percent of respondents indicated that during the 2020 wildfire season they were concerned about the effects of smoke on their health. A similar percentage indicated that they were concerned about the health of vulnerable people. High-exposure respondents (those who reported that they were exposed to five or more days of wildfire smoke per year) from recruitment A were more likely to indicate health concerns than respondents who reported less exposure. However, rural respondents from recruitment A were less likely than urban respondents to indicate health concerns.

Preparedness for the 2020 Wildfire Smoke

Nineteen percent of respondents from recruitment A reported that they were prepared for the 2020 wildfire smoke event before it happened, and 68 percent reported that they were not prepared. By contrast, approximately 85 percent of the target Hispanic and Latinx survey respondents (recruitment B) reported that they were prepared for the 2020 smoke event. Across recruitments, 72 percent of the 378 individuals who felt prepared reported that previous experience with smoke contributed to their preparedness. High exposure and rural populations from recruitment A were statistically more likely to indicate that prior experience contributed to their preparedness. Across recruitments, 63 percent of respondents indicated that they already had emergency supplies at home, and 53 percent indicated that their community had a response plan for wildfire and smoke. Among respondents who said they were not prepared or were unsure, 62 percent said they would have felt more prepared if they had access to adequate household protections such as air filters, doors and windows that seal, and emergency supplies. About 53 percent said they would have felt more prepared if they had access to information about the possibility of a smoke event, and just under 50 percent said they would have felt more prepared if they had access to personal protective equipment such as respirators, masks, and asthma medications. Within recruitment A, lower-income populations, non-homeowners, and vulnerable populations were more likely to indicate that access to clean air shelters would have made them feel more prepared.

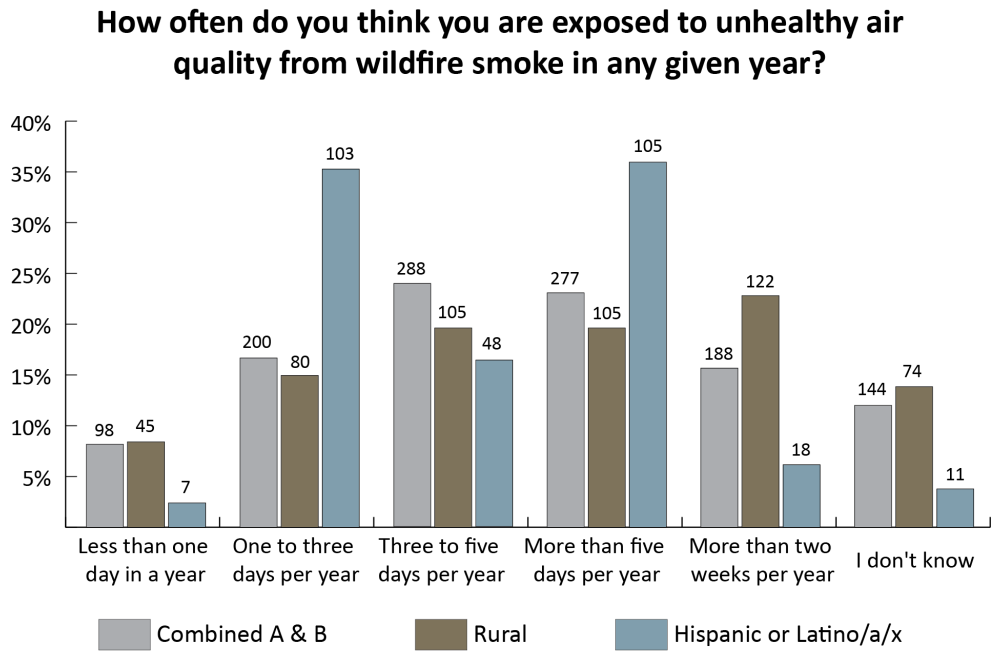

Figure 4. Self-assessed annual exposure to wildfire smoke across recruitments A and B. X-axis, perceived annual frequency of smoke exposure; Y-axis, percentage reporting. Numbers above each bar indicate the number of respondents who selected each option.

Protective Action Responses to Smoke During the 2020 Wildfire Season

Most respondents in both recruitments (77 percent) reported that they took protective measures or changed their daily routine while outdoors. However, lower-income respondents were less likely to indicate that they took protective actions, as were non-homeowners from recruitment A. These lower-income and non-homeowner populations were less likely to indicate that they stayed home, avoided going outside, or reduced their total time outdoors. Similarly, rural populations from recruitment A were less likely to report that they avoided or reduced time spent outdoors or used an N95 mask, KN95 mask, or respirator. Nevertheless, high exposure and vulnerable populations were more likely to indicate that they took protective measures outdoors. For example, vulnerable populations were more likely to indicate that they used an N95 mask, KN95 mask, or respirator outdoors, whereas high exposure populations were more likely to indicate that they used other types of masks, such as cloth or surgical masks used to prevent the spread of COVID-19.

A clear majority of respondents from recruitment B (95 percent) said they took protective actions while indoors. However, fewer than half of respondents from recruitment A (42 percent) said they took protective measures while indoors. Again, lower-income respondents in recruitment A were less likely to say they took protective actions indoors. Rural respondents from recruitment A were less likely to have used a portable, high efficiency particulate air (HEPA) filter. In comparison, vulnerable populations from recruitment A were more likely to have used a portable HEPA air purifier or a homemade box fan HEPA air filter. High exposure populations from recruitment A were more likely to have installed a commercial HEPA heating, ventilation, and cooling (HVAC) air system, and high exposure populations from recruitment B were more likely to have created a cleaner air space in their home or have used an N95 mask, KN95 mask, or respirator in their home.

Informational Preferences and Needs

Most respondents (63 percent) indicated that they relied on their observations to provide information about air quality during the 2020 wildfires. Among media sources, the internet (websites, email, social media) was selected by 67 percent of respondents, and television was chosen by 58 percent of respondents. High exposure populations from both recruitments were more likely to select multiple sources of information, including television and friends and family. Within recruitment A, lower-income and rural populations were less likely to choose television. Populations other than White and Hispanic/Latinx in recruitment A were more likely to select friends or family.

Most respondents (79 percent) indicated that they would like more forecasts related to air and smoke conditions. Many respondents also said that they would like more information about how to stay safe indoors (58 percent), how to stay safe while engaging in outdoor activities (52 percent), and personal protective equipment (55 percent). Members of high exposure populations from recruitment A, respondents with a preference for Spanish from recruitment B, and respondents living with disabilities from recruitment B were more likely to indicate multiple informational needs.

Discussion

Survey Limitations and Caveats

We acknowledge that our sample was limited to people who regularly use the internet, therefore excluding those who lack access and ability to use the internet and those who choose to avoid internet use. Furthermore, because recruitment A was administered via a commercial internet survey panel audience, we cannot verify that the sample truly represents Oregon residents. According to the American Community Survey, from 2016–2020, 9.9 percent of people in Oregon were living with a disability. By contrast, 45 percent of respondents to our survey reported living with at least one disability. We suggest that this apparent oversampling of individuals with disabilities may relate to how the commercial panel recruited and maintained their audience. We observed similar issues related to recruitment B. Because recruitment B was distributed through a Facebook advertisement that relied on preexisting social networks and offered a monetary incentive, the sample did not represent Hispanic/Latinx Oregon residents. Indeed, recruitment B sampled a population with unusually high exposure to wildfire smoke, experience with wildfire evacuation, and preparedness for smoke events. Half of the respondents from recruitment B still reside in communities that were under evacuation orders during the 2020 wildfires (Talent and Phoenix, Medford, and McKenzie River). Others, we suspect, were part of the diaspora that resulted from the loss of homes during those fires. Therefore, recruitment B responses must be interpreted within this context.

Concerns About Smoke

Consistent with previous findings (Ellison et al. 2021), we found that most respondents were concerned about the impacts of smoke on their health or the health of vulnerable people. On the one hand, although it is relatively novel for people to be concerned about ephemeral and superficially innocuous hazards such as wildfire smoke, our survey demonstrated that increased exposure to smoke is correlated with health concerns. On the other hand, this effect may vary on the basis of geography. For example, although rural respondents may be more exposed to wildfire smoke for longer durations during the year, they were less likely to be concerned about the effect of smoke on their health or the health of vulnerable populations.

Preparedness for Smoke

Previous experience with smoke also appeared to correspond with people's level of preparedness for coping with wildfire smoke. For those who were not prepared for the 2020 smoke event, increased availability and access to adequate household protections, information about the possibility of a smoke event, and access to personal protective equipment would contribute to better preparedness. These results suggest the need to increase the number and reach of public programs focused on dissemination of smoke-related information as well as programs that assist in the distribution of air filtration devices such as HEPA air filters, HEPA HVAC systems, and masks that filter $PM_{2.5}$. It also is evident that there is a demand among lower-income populations, non-homeowners, and vulnerable populations for public access to clean air shelters. For some populations (e.g., outdoor workers), staying indoors with filtered air is not an option. We highlight this as a key area for public health focus as exposure to wildfire smoke increases in the Pacific Northwest (see, for example, the state of Oregon's rules to address employee exposure to wildfire smoke: osha.oregon.gov/OSHAPubs/factsheets/fs92.pdf).

Protective Action Responses

Although most of our respondents indicated that they took some protective actions during the 2020 smoke event, most actions applied to outdoor activities. Less than half of respondents within recruitment A indicated taking protective measures indoors. The lack of protective actions was even more pronounced for lower-income populations from both recruitments. This suggests a need to improve communication and outreach about how people can improve their indoor air quality during a wildfire smoke event. Furthermore, informational outreach to lower-income populations and non-homeowners may need to be paired with programs that provide assistance with the purchase of upgrades for HVAC systems, stand-alone air purifiers, and other protective equipment.

Informational Needs

Given that most respondents indicated that they relied on their observations to inform them about smoke, it appears that people were tracking changes in air quality on some level. However, some of the most volatile pollutants from smoke are invisible to the naked eye, and accurate air quality assessments require more-sophisticated instrumentation. The availability of local to regional air quality monitoring sensors and resulting dissemination of information has markedly improved in recent years with advances in cellphone, internet, and computing technologies. In addition, most respondents indicated that they would like to have more information on smoke conditions and forecasts of smoke. Although there are numerous options for obtaining air quality information, such as smartphone apps and text alerts, reaching a wider audience with timely information may require additional creative efforts in a range of culturally appropriate modalities.

Acknowledgments

This research was supported in part by a University of Oregon Seed Funding Grant (Huber-Stearns, Coughlan, Smith, and Clark) and funding for a statewide evaluation from the Oregon Health Authority.

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Coastal Hazards

Felicia Olmeta Schult, Peter Ruggiero, Meredith Leung, and Mohsen Taherkhani

The changing climate will continue to affect hazards along the coast and estuarine shorelines of Oregon, with social and economic effects on coastal communities. Property owners, businesses, and local governments will need to respond to these hazards and impacts while evaluating trade-offs between public and private interests. Recent assessments, analyses, and reports have documented increasing rates of sea-level rise and erosion along Oregon's coasts, and measures are being implemented or considered to adapt to these changes.

Observed and Projected Trends in Sea Level

The Oregon coast is within Cascadia, which is defined by the subduction of the Juan de Fuca Plate under the North American Plate. The imminent rupture of the Cascadia Subduction Zone will greatly affect the Oregon coast's inhabitants, infrastructure, and ecosystems. The probability of a Cascadia-wide, tsunami-generating earthquake in the next 50 years is approximately 15–25 percent, and the probability of a partial rupture on the southern Oregon coast is about 37–43 percent (Atwater 1987, OSSPAC 2013, Frankel et al. 2015). Tectonics has a substantial effect on the region's exposure to chronic coastal hazards through its influence on geomorphology and rates of relative sea-level rise (Burgette et al. 2009, Komar et al. 2011).

Primarily due to tectonic uplift, relative sea-level rise rates are slower in Oregon than in many other coastal regions of the United States. In some areas of the Oregon coast, tectonic uplift has kept pace with increases in sea level. However, relative sea-level rise rates along much of the Oregon coast are at least 1 mm per year less than the current global average (~3.4 mm [0.13 in] per year; Sweet et al. 2022). For example, whereas relative sea level in southern Oregon (Coos Bay and south) and northern Oregon (Cannon Beach and north) is either falling slightly or stable, relative sea-level rise rates in central Oregon have been 1–3 mm (0.04–0.12 in) per year since at least the 1970s (Komar et al. 2011). Developing high-resolution estimates of alongshore vertical uplift rates, which affect local projections of relative sea-level rise and chronic coastal hazards, is a high priority.

The National Oceanic and Atmospheric Administration (NOAA) recently released regional sea-level rise scenarios for the United States coastline from 2000–2150 that incorporate the best estimates of uplift at a resolution of one degree (about 111 km [69 mi]) (Sweet et al. 2022). By 2050, the expected rise in sea level will cause total water levels to increase and change coastal flood regimes throughout the United States, with major and moderate high-tide flood events occurring as frequently as moderate and minor high-tide flood events occur today. The emissions-based, probabilistic sea-level rise projections included low (0.3 m [1 ft] of global mean sea level rise by 2100), intermediate-low (0.5 m [1.6 ft.]), intermediate (1.0 m [3.3 ft]), intermediate-high (1.5 m [4.9 ft]), and high (2.0 m [6.6 ft]) scenarios. These projections (Table 1), combined with observed sea-level rise at NOAA tide gauges in South Beach and Astoria, Oregon, highlight the wide range of sea-level rise expected along this tectonically active coastline (Figure 1).

Effects of Climate Change on Storminess Patterns

Substantial uncertainties hamper quantification of how climate change will affect storminess patterns. The El Niño-Southern Oscillation is a key driver of interannual global climate variability. El

	Year								
	2040			2070			2100		
City	Low	Intermediate	High	Low	Intermediate	High	Low	Intermediate	High
Port Orford	6	11	16	11	32	78	16	79	182
Charleston	7	11	17	13	33	78	18	81	183
Newport	9	14	19	17	37	82	25	87	187
Astoria	3	7	12	6	25	68	9	69	167

Table 1. Projected sea-level rise (cm) over time at four cities in Oregon given scenarios of low (0.3 m [1 ft]), intermediate (1.0 m [3.3 ft]), and high (2.0 m [6.6 ft]) global sea-level rise (Sweet et al. 2022).

Niño events, which are characterized by considerable warming of sea surface temperatures in the central and eastern equatorial Pacific (Lindsey 2009), affect the physical drivers of coastal hazards during winter storms in the Pacific Northwest, such as variation in wind direction, increased wave energy, and elevated water levels along the coast (Barnard et al. 2015). The frequency, intensity, and location of El Niño events vary within the Pacific Ocean basin, and forecasting of El Niño events and their future climatology is an area of active research (e.g., Yan et al. 2020). Historically, major coastal flooding and erosion along the Oregon coast was more likely during El Niño years (e.g., Barnard et al. 2015). Due to anomalies in physical processes, such as elevated water levels and higher wave energy from the southwest, local erosion along the west coast of the United States tends to be high during major El Niño seasons. For example, many of the beaches in Tillamook County eroded substantially and either took many years to recover, or have not yet recovered, from the effects of the 1997–1998 El Niño and the severe winter of 1998–1999 (Ruggiero et al. 2013). Areas of erosion included the village of Neskowin immediately north of Cascade Head, Rockaway Beach, and Cape Lookout State Park (Ruggiero et al. 2013). The most recent major El Niño event (2015–2016) caused the average seasonal erosion on the Oregon coast to be up to 30 percent greater than the previous year. Coastal flooding and erosion deplete sand from beaches and make them more susceptible to elevated water levels and enhanced wave energy during future storms. Higher precipitation rates during El Niño seasons can increase runoff and compound flooding hazards by elevating the local sea surface.

Despite growing attention to improving data and modeling techniques, there is considerable uncertainty about climate change-induced shifts in long-term trends in the frequency and intensity

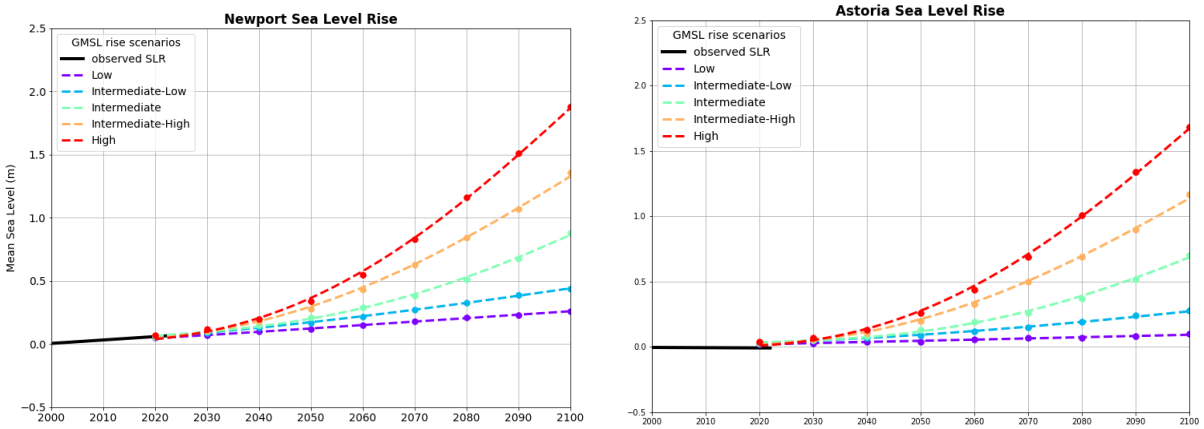

Figure 1. Observed and projected regional sea-level rise (Sweet et al. 2022) from 2000 through 2100 at two tide gauges in Oregon. Local tectonic and hydrodynamic processes affect differences among local projections.

of extreme El Niño events (Collins et al. 2010). One study projected that the magnitude of El Niño events in the twenty-first century would be indistinguishable from those in the twentieth century (Stevenson 2012), whereas another found that the frequency and intensity of extreme El Niño events may increase by as much as 100 percent by 2100 (Cai et al. 2015), potentially intensifying hazards along the Oregon coast. It also has been suggested that the strength of El Niño will weaken over millennia as carbon emissions increase (Callahan et al. 2021).

Effects of Climate Change on Coastal Erosion and Flooding

Relative sea-level rise narrows the gap in elevations between commonly occurring high tides and the thresholds above which coastal flooding and erosion begin. Therefore, increases in extreme coastal water levels along the Oregon coast increase coastal erosion and coastal flooding impacts.

			Percentage of transects eroded, 2002–2016		
Littoral cell (south to north)	**2002–2016 (m/year)**	**1967–2002 (m/year)**	**Total**	**More than -1 m / year**	**More than -3 m / year**
Brookings	-1.50 ± 0.04	-0.05 ± 0.10	90	59	18
Pistol	-1.10 ± 0.06	0.50 ± 0.10	75	56	11
Gold Beach	-1.60 ± 0.03	0.60 ± 0.10	83	63	22
Nesika	-0.70 ± 0.30	-0.40 ± 0.20	67	41	8
Humbug	-0.50 ± 0.03	-0.40 ± 0.10	81	24	0
Port Orford	-1.00 ± 0.03	-0.30 ± 0.10	64	41	23
Bandon	-0.60 ± 0.03	0.20 ± 0.10	65	40	7
Coos	-1.00 ± 0.03	0.03 ± 0.10	75	52	11
Heceta	-0.20 ± 0.05	-0.10 ± 0.10	60	26	0
Newport	0.20 ± 0.04	-0.50 ± 0.10	50	24	2
Beverly	-1.00 ± 0.08	-1.1 ± 0.10	84	55	0
Lincoln	-0.80 ± 0.03	-0.30 ± 0.10	71	50	10
Neskowin	-1.90 ± 0.06	-1.10 ± 0.10	85	70	27
Sand Lake	0.50 ± 0.10	-0.50 ± 0.10	36	20	1
Netarts	-0.40 ± 0.10	-1.00 ± 0.10	65	28	0
Rockaway	0.02 ± 0.06	0.60 ± 0.10	44	25	7
Cannon Beach	0.30 ± 0.08	-0.50 ± 0.10	39	13	4
Clatsop	0.30 ± 0.02	1.90 ± 0.10	40	19	1
Oregon average	-0.70 ± 0.01	0.03 ± 0.02	65	42	9

Table 2. Average rates of shoreline change (meters per year) along the Oregon coast from 2002–2016 and associated uncertainties (Light 2021). Red, statistically significant erosion; blue, statistically significant accretion. Average rates of shoreline change and values from 1967–2002 from Ruggiero et al. 2013.

A multi-decadal, statewide analysis identified both a general increase in shoreline erosion along the Oregon coast in recent decades and significant spatial variation within and among littoral cells (coastal compartments within which sediment movement is self-contained) (Light 2021). Shoreline change was statistically significant in seventeen of the eighteen primary littoral cells (all but Rockaway) along the Oregon coast from 2002–2016 (Table 2). Furthermore, the shoreline in five littoral cells in southern Oregon (Coos, Bandon, Gold Beach, Pistol, and Brookings) accreted from 1967–2002 but eroded from 2002–2016. By contrast, shorelines in three littoral cells in central and northern Oregon (Newport, Sand Lake, and Cannon Beach) eroded from 1967–2002 and accreted from 2002–2016. The average statewide rate of change from 2002–2016 was -0.7 m (-2.3 ft) per year; 65 percent of locations (transects) studied eroded, and 42 percent eroded at rates more than 1 m per year. The highest average erosion rates tended to be in southern Oregon. A larger percentage of transects in Oregon eroded during 2002–2016 (65 percent) compared to the 1967–2002 period (54 percent).

Figure 2. Coastal erosion at Gleneden Beach, Lincoln County, March 2021. Photograph by Hailey Bond.

Additionally, although erosion exceeded -1 m (-3.3 ft) per year in 18 percent of transects along the Oregon coast from 1967–2002, erosion exceeded -1 m per year in 42 percent of transects from 2002–2016 (Figure 2). Estimates of shoreline change from 2002–2016 (Light 2021) likely include the impacts of the major 2015–2016 El Niño event and are therefore biased toward erosion.

Taherkhani et al. (2020) used data from tide gauge stations and projections of future sea-level rise (Kopp et al. 2014) to investigate continuous shifts in flooding along coastlines in the United States. They found that approximately 7 cm (2.8 in) of sea-level rise along the Oregon coast doubles the odds that annual flood levels will exceed the 50-year event threshold (a level with a 2 percent chance of occurring in a given year). The odds of this magnitude of flooding double approximately every 6 years until 2075. These results were based on the high emissions scenario in Sweet et al. (2022) and assumed climate stationarity.

Effects of Coastal Hazards on Communities and Infrastructure

Increases in water levels due to sea-level rise and possible changes in patterns of storminess will increase the frequency and magnitude of coastal erosion and flooding (e.g., Figure 3). Below, we highlight potential effects on coastal communities and infrastructure and efforts being implemented or considered to adapt to these hazards.

Figure 3. Coastal flooding in Nehalem, Oregon, on 6 November 2021. Photograph by Tyler Sloan, Oregon King Tides Project (CC BY-NC-SA 2.0).

The U.S. Army Corps of Engineers used Climate Central's (2021) Surging Seas Risk Finder to estimate the potential effects of 1 and 2 feet (0.3 and 0.6 m) of sea-level rise on populations, land, property, and infrastructure within the United States (USACE 2022). On the Oregon coast, approximately 781 homes and 1318 people are

within the area that would be inundated by 1 foot of sea-level rise (Table 3) (USACE 2022). An estimated 18 percent of those individuals have high social vulnerability as estimated on the basis of 29 variables related to wealth, racial and social status, ethnicity, age, health insurance, special needs, ethnicity, employment, and gender. An additional 307 homes and 627 individuals, 157 of them with high social vulnerability, are located within the area that would be inundated by 2 feet of sea-level rise.

	Below 1 foot	Below 2 feet
Population	1318	1945
High social vulnerability population	238	395
Homes	781	1088
Roads (miles)	30	51
Wastewater treatment sites	12	14
Land (square miles)	58	75
Protected land (square miles)	15	20

Table 3. People, infrastructure, and land in Oregon below 1 and 2 ft (0.3 m and 0.6 m) of sea-level rise (data source: Climate Central 2021; table adapted from USACE 2022). These estimates should be used for planning-level purposes only. The values in the table may overestimate or underestimate exposure to flooding. Protected land records are from the U.S. Geological Survey. Protected areas are those dedicated to the preservation of biological diversity and to other natural, recreational, and cultural uses, and managed for these purposes through legal or other effective means.

In 2018, the Oregon Department of Geology and Mineral Industries (DOGAMI) assessed the risks of natural hazards to the communities of Coos County, Oregon (Williams et al. 2021). This risk assessment estimated that 1870 buildings will be damaged by a 100-year flood scenario (i.e., 1 percent chance of flooding in a given year), causing an estimated loss of $125 million, damage to 13 critical facilities, and displacement of as many as 2116 individuals. For example, 95 percent of flood-exposed buildings in the City of Coos Bay are not elevated above the 100-year flood level. The assessment's analysis of whether a building is within or outside of a hazard zone also estimated the number of people whose mobility may be limited by floodwaters. Many residents in the cities of Coos Bay (773), Lakeside (253), and Myrtle Point (119) may need evacuation assistance during a flood.

Figure 4. Coastal erosion at Beverly Beach and U.S. Highway 101, Lincoln County, Oregon, February 2021. Photograph by Hailey Bond.

Sea-level rise on the Oregon coast also may lead to changes in navigation channels (e.g., leading to an increase in dredging and adjustment of channel location and dimensions), increased scouring at structure foundations, and decreased clearance under bridges and port infrastructure (USACE 2022). U.S. Highway 101 and other major transportation routes and facilities along the Oregon coastline will become increasingly susceptible to erosion, flooding, and landslides as climate changes (Figure 4). The Oregon Department of Transportation has supported research with the aim of enhancing the resilience of Highway 101 to coastal hazards (Box 1).

Approaches to Coastal Climate Change Adaptation

Many climate-change adaptation measures are being implemented or considered in coastal Oregon. These include hard structures (gray infrastructure), soft structures (natural and nature-based features), a combination of hard and soft structures, and nonstructural measures (e.g., policies and regulations) (Table 4). Hard structures are typically designed to armor the backshore to prevent erosion landward of the structure (e.g., riprap revetments). Soft structures, such as salt marsh restoration, beach nourishment, and dynamic cobble revetments, are intended to maintain or restore the shoreline by mimicking natural processes (USACE 2022). The function and performance of new hard and soft structures will be affected by sea-level rise. For example, increased wave attack associated with sea-level rise may reduce the stability of hard protective structures (USACE 2022). Sea-level rise will also likely erode foredunes, potentially necessitating repeated nourishment.

Substantial efforts are underway to use dredged sediments and soft structures (e.g., dynamic revetments, dune restoration) instead of shoreline hardening to maximize ecological benefits. For example, a dynamic revetment is dissipating wave energy and slowing erosion at Cape Lookout State Park (Figure 5) and the Columbia River South Jetty.

Structural adaptations		
Type	**Strategy**	**Description**
Hard structures	Jetties	Jetties extend into a body of water to direct and confine a stream or tidal flow to a selected channel and to limit shoaling of the channel. Jetties at the entrance of a bay or river also protect the entrance channel from storm waves and crosscurrents.
	Riprap revetments	A layer of stone intended to limit erosion and create hard armoring (Johannessen et al. 2014).
	Seawalls	Concrete structures that are built to withstand storm waves and protect costly infrastructure.
	Dredging	Primary method of managing sediment accretion along harbors, ports, and jetties to maintain draft for ship traffic and channel depth for navigation. In some cases, the dredged material is used rather than deposited offshore.
Soft structures	Wetland and salt marsh restoration, enhancement, or creation	Creation of a wetland on a site that was historically non-wetland, rehabilitation of a degraded wetland, or reestablishment of a wetland so that soils, hydrology, vegetative community, and habitat are a close approximation of the original natural condition that existed prior to modification to the extent practicable (USDA 2021). Among the benefits of wetlands and salt marshes are flood-risk reduction and buffering against erosion of adjacent uplands.
	Dune restoration, replenishment	Dune grass planting, fencing, and other techniques to trap sand.
	Beach nourishment	Replenish eroding beaches while maintaining recreational uses and habitat that would be lost with a hard structure. May involve use of dredged materials (Stronkhorst et al. 2018).
	Use of dredged materials	Intentional placement of dredged sediment to provide economic, environmental, and societal benefits by supporting beach nourishment, wetland construction, and replenishment of the littoral zone (Gailani et al. 2019).
	Dynamic revetments or cobble berms	Gravel or cobble beaches constructed at the shore in front of a property to be protected. The sloping, dynamic, porous cobble beach disrupts and dissipates wave energy (Allan et al. 2005).
Nonstructural adaptations		
Type	**Strategy**	**Description**
Policies	Zoning restrictions	Reduce the number of structures built in high-risk zones. Require developers to construct structures that are more resilient to erosion, flooding, or other expected impacts of climate change.
	Managed retreat	As the shoreline migrates inland, move people, critical facilities, and structures further inland to avoid coastal hazards.

Table 4. Approaches to coastal climate-change adaptation (modified from USACE 2022).

Knowledge Gaps and Adaptation Efforts

Knowledge Gaps and Needs

Figure 5. Dynamic revetment at Cape Lookout State Park, Tillamook County, Oregon, March 2021. Photograph by Hailey Bond.

The U.S. Army Corps of Engineers recently compiled research and management recommendations, actions, and needs from regional stakeholders and tribal partners to improve coastal resilience to current and future climate change in the Pacific Northwest (USACE 2022). Stakeholders indicated a clear need for sustained monitoring of shoreline change, increased frequency of airborne LIDAR surveys, and digital open-source repositories of regional shoreline-change data. High-priority research includes the prediction of future shoreline erosion and accretion from multiple stressors. Although concentrations of accretion and erosion are known, sediment sources, sinks, and transport pathways in Pacific Northwest estuaries are not well quantified. A better understanding of sediment movement and sediment budgets would improve overall sediment management, inform dredging in Pacific Northwest estuaries, and create opportunities for use of dredged sediments. Furthermore, standardized criteria for evaluating project success are needed to understand the geophysical, ecological, economic, and cultural impacts of projects.

In Oregon, over 3500 oceanfront parcels without shoreline armoring, about 40 percent of the oceanfront parcels in the state, are eligible to install armoring (Beasley and Dundas 2021) because they were developed before 1977. Ongoing public engagement and outreach are necessary to inform property owners about the anticipated evolution of the coastal zone and trade-offs associated with shoreline management options (Mills et al. 2018). Given that shoreline management decisions have diverse environmental, economic, and community impacts, a single infrastructure investment is unlikely to result in sustainable long-term shoreline management. Integrating shoreline management with coastal resilience planning can improve emergency response plans, habitat restoration plans, and community development.

Technical and financial support is needed by small, under-resourced, and traditionally under-represented communities that struggle to apply for planning and implementation grants to adaptively manage their shorelines. Barriers include matching-fund requirements and traditional National Economic Development Plan benefit-cost analysis ratios. Some of these communities have high relative social vulnerability and will face disproportionate burdens of coastal flooding and hazards.

Potential flood mitigation by wetlands is well established in the literature. However, reduction in flood risk by wetlands restoration in the region to date, and by potential future restoration under a range of sea-level rise scenarios, is not well understood. State and federal agencies and

Box 1. Monitoring and adaptation along U.S. Highway 101

The Oregon Department of Transportation commissioned two research projects with Oregon State University to inform their proactive management of sea-level rise induced sea cliff erosion, landslides, and flooding on U.S. Highway 101. The first project used advanced sensors to monitor and evaluate stability and activity of steep sea cliffs and slopes due to climate change at five sites where

Figure B1. Damage resulting from a landslide along an unstable, erosion-prone section of U.S. Highway 101 south of Port Orford, Oregon (June 2022). Photograph by Michael Olsen.

erosion has been prevalent (Senogles et al. 2022). The second project evaluated hazards at over 70 sites on Highway 101 and prioritized the sites on the basis of their levels of risk (Alberti et al. 2022). At five of those sites, the project quantified the benefits and costs associated with alternatives such as no mitigation and eventual loss of that section of highway, rerouting, natural revetments, and different levels of structural accommodation.

In addition to informing potential revisions of state planning goals, this research is building a common understanding of risks and needs associated with the management of coastal hazards and building partnerships among federal, state, and local stakeholders, which include the Federal Highway Administration, Oregon Department of Geology and Mineral Industries, Oregon Parks and Recreation Department, and Oregon Department of Land Conservation and Development. Furthermore, the research addresses the resilience and reliability of Oregon's transportation system for the traveling public.

nongovernmental organizations participating in wetlands restoration in the region note that information is inadequate to support planning and engineering for natural and nature-based features in the Pacific Northwest (Janousek et al. 2019).

Project and Resource Highlights

Many recent and ongoing efforts in Oregon aim to increase understanding and knowledge of the effects of climate change on coastal hazards and promote actions to create and maintain resilient coastal communities. These projects and resources target diverse audiences, including coastal homeowners, businesses, visitors, planners, scientists, communities, state agencies, and tribal staff.

The Oregon Climate Change Adaptation Framework identifies high-priority climate risks, their expected impacts, and short-term actions by which state agencies might reduce these risks. Actions addressing sea-level rise include updates to the state's residential design standards and building codes in floodplains and acquisition of homes at risk from coastal flooding. The updates to the floodplain design standards and residential building codes now require that structures constructed in coastal high-hazard areas be elevated by at least 1 foot (0.3 m) above the 100-year flood base elevation, and prohibit the construction of basements (DLCD 2021).

The Cascadia Coastlines and Peoples Hazards Research (CoPes) Hub, funded by the U.S. National Science Foundation, seeks to inform and enable integrated hazard assessment, mitigation, and adaptation—including comprehensive planning, policy-making, and engineering—through targeted scientific advances in collaboration with communities. The processes that the Cascadia CoPes Hub is studying include increasing total water levels due to climate change, coastal erosion trends, subduction megaquake frequency, movement of debris by tsunamis, best management practices to maintain connections among coastal communities and protect the communities from hazards, and exclusionary, regional risk governance processes. To achieve equitable and just outcomes, the Cascadia CoPes Hub strives to respect and incorporate traditional and local ecological knowledge.

The Oregon Department of Land Conservation and Development's Oregon Coastal Management Program received funding from the National Fish and Wildlife Foundation's Coastal Resilience Fund to engage coastal communities in Coos and Tillamook counties in identifying resilience needs and planning estuary restoration projects. The aims of the process include empowering local communities to implement coastal resilience activities and increasing local understanding of trade-offs among coastal resilience projects (M. Reed, personal communication).

In addition to clarifying what is and is not a beachfront protective structure, the Oregon Coastal Management Program's erosion control guidebook provides information on Statewide Planning Goal 18 (beaches and dunes), the policies and land-use goals most relevant to the Oregon coast, typical and atypical permitting processes for erosion control, and details about erosion control measures that are viable for the Oregon coast. Implementation requirement 5 of Statewide Planning Goal 18 limits the placement of beachfront protective structures to areas that were developed before January 1977. This policy effectively places a cap on the amount of ocean shore that may be hardened, and therefore limits the cumulative impacts of such hardening. Shoreline armoring fixes the shoreline in place, traps sediment, and causes scouring and lowering of the beach profile. Over time, these actions can lead to the loss of Oregon's public beaches. The Oregon Coastal Management Program also is developing a guide for local coastal jurisdictions to evaluate risks from sea-level rise and potential adaptation strategies consistent with Oregon's existing regulations (M. Reed, personal communication).

Information, strategies, and lessons learned from mitigation, adaptation, and preparedness projects along the Oregon coast are not always effectively shared among stakeholders. Therefore, Oregon Sea Grant developed the Oregon Coastal Hazards Ready (OCHR) Library & Mapper (bit.ly/OCHR-Mapper), an ArcGIS StoryMap that displays 39 case studies of coastal hazards preparedness (Oregon Sea Grant 2021). The Mapper is designed to assist individuals, communities, and tribal and local governments in identifying approaches to prepare for acute and chronic coastal hazards. In partnership with the Cascadia CoPes Hub and the Washington Department of Ecology, Oregon Sea Grant sends a monthly Pacific Northwest Coastal Hazards Resources Newsletter to the OCHR Mapper listserv, which has more than 100 subscribers.

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The Economic Implications of Climate Change for Oregon

Steven J. Dundas, Susan Capalbo, and James Sterns

Assessments of the economic impacts of a changing climate on key sectors in Oregon and the Pacific Northwest have been included in previous Oregon Climate Assessments (Dello and Mote 2010; Dalton et al. 2013, 2017; Mote et al. 2019; Dalton and Fleishman 2021). The first and second Oregon Climate Assessments provided in-depth overviews of the methods and approaches used to value these impacts and the challenges and opportunities to designing policies to enhance mitigation and adaptation. Collectively, the previous five assessments provide content on the economic impacts that remains pertinent, and we encourage readers to refer to them for further background on methods and regional economic impacts.

Here, we update previous Oregon Climate Assessments in two ways. First, we provide a more robust discussion of economic concepts and tools to better understand Oregon's climate challenges and opportunities and associated public policies and programs. Second, we highlight recent insights on climate change impacts as they relate to Oregon sectors and economic activity or to similar sectors in the Pacific Northwest. This chapter begins with a few observations from past research that are brought to bear on the design of our economic assessment efforts, continues with a discussion of climate change economics and policy tools, and then presents an update on sector-specific economic impacts in Oregon and the region.

Two Decades of Research

Oregon's economy and gross domestic product (GDP) remain highly impacted by the changing climate (e.g., increases in temperature, increased variation in the timing and intensity of precipitation). As noted in the first Oregon Climate Assessment (Dello and Mote 2010), it is nearly impossible to provide a comprehensive economic assessment of the effects of climate change on Oregon due to the breadth and diversity of Oregon's natural-resource based economy; the complexity of the interactions among sectors, climate variables, and climate-related variables; and limited empirical assessments in key areas, such as public health, migration, and sector-specific agricultural markets. Prior Oregon Climate Assessments also emphasized that many assessments have sidestepped the issue of behavioral responses and instead projected economic impacts under business-as-usual scenarios. Although business-as-usual projections provide useful information, they are best viewed as an upper bound on costs or impacts of climate change, capturing the likely impacts assuming that groups such as producers, stakeholders, and land managers do not adapt or respond to changing economic, social, biological, or physical conditions.

Over the past decade, frameworks for conducting economic assessments and for integrating site-specific evidence on the level and extent of changes in underlying biological and physical conditions into empirical findings have improved. Real-time, site-specific economic and behavioral data, better data-transfer technologies, and increases in the breadth and resolution of biological and physical information contribute to a more robust foundation of information for these assessments. Increases in stakeholder engagement are providing stronger pathways to understand and design effective policies for addressing climate change at local and transformative extents (Moore et al. 2017, Auffhammer 2018, Antle 2019). Furthermore, behavioral responses to extreme climate events that are being observed in real time can serve as the basis for ground-truthing and refining economic frameworks and predictions.

The magnitude of regional impacts of climate change hinges on the magnitude of the impacts (i.e., net costs) to local communities and businesses, changes in natural assets and ecosystem services, and behavioral responses both to these climate-induced changes and to climate policies and programs. Economists have made substantial progress in addressing the challenges associated with estimating the cost of climate impacts and valuing changes in ecosystem services and natural capital. The information in this section on key sectoral impacts in Oregon and the Pacific Northwest is testimony to such efforts. Applying sound economic principles and values to ecosystem changes conveys to society that ecological services contribute to human well-being (Figure 1). As noted nearly 25 years ago by Geoffrey Heal (1998:3), "we are coming to realize, in part through the process of losing them, that environmental assets are key determinants of the quality of life."

Figure 1. Changes in the timing and form of precipitation have substantial effects on Oregon's economy and the well-being of its residents. Photograph by Erica Fleishman.

Climate Change Economics and Policy Tools

Much of the current economy involves, directly or indirectly, the combustion of fossil fuels, which results in emissions of greenhouse gases (GHGs). The core economic problem with GHG emissions is that those who produce the emissions do not pay for that privilege, and those who are harmed are not compensated. Since the beginning of the industrial revolution, Earth's atmosphere and oceans have been treated as free resources that absorb emissions from industrial activity.

When one buys corn from a supermarket, they pay for the costs of producing the corn, and the farmers and retailers are compensated for their provision of the corn to the consumer. But when production of that corn requires the combustion of fossil fuels, whether to pump the water that irrigated the corn field or to fuel the truck that delivered the corn, an important cost is not covered: the social damage caused by GHGs that are emitted. Economists call such costs *externalities* because they are external to the market. An externality is a byproduct of economic activity that causes damages to a third party that did not participate in the market transaction.

Modern life is full of externalities. Some are harmful, such as when runoff of agricultural fertilizer enters a river, kills fish, and degrades water quality. Others are beneficial, such as when researchers discover a polio vaccine. Climate change is likely the most complex of all externalities because it involves so many activities, affects the entire planet, has enduring effects, and no individual can do much to slow the changes.

Economics teaches one major lesson about externalities: markets that fail cannot solve the problems they generate. In the case of externalities from GHG emissions, unregulated markets produce too

much because markets do not put a price on the external damages from those emissions. The market price of gasoline does not include the costs imposed on society by GHG emissions, and so gas is cheaper, people drive more, and more emissions are generated. Because an unregulated market sets prices incorrectly, governments must step in and regulate, control, or tax the activities that have significant harmful externalities. Climate change is no different from other externalities: it requires considerable governmental action to reduce harmful spillovers. This leads to a second economic challenge: a collective action problem. This problem arises when the best outcome for all would be cooperation to solve climate challenges, but many individuals, firms, and governments choose their own economic best interests, which often conflict with joint actions.

Economic Challenges to Effective Policy Decisions

Addressing the externalities that contribute to climate change, and the collective action needed for effective climate policies, present distinct challenges for five core economic reasons: the need for global cooperation, scale and irreversibility of impacts, intergenerational nature of impacts, uncertainties involved in climate systems and estimation of impacts, and unequal distribution of those impacts. In other words, the effects of climate change are likely to be costly, irreversible, unequally distributed, and experienced by current and future generations. Definition of policy goals must address uncertainties in future outcomes and the global nature of the problem.

These five challenges are complex and sometimes daunting to overcome. Regardless of where GHGs are emitted, they mix uniformly into the atmosphere and cause problems for all. Incentives exist for a collective action problem in climate change mitigation efforts because economic damage may not occur in the country that generated the emissions, and the emissions-generating country may not benefit from incurring expenditures to mitigate the problem. Low-income countries have argued that high-income countries have historically received a large share of the benefits of GHG emissions and should now bear the costs of mitigating climate damages.

Because climate change does not respect national boundaries, effective policy solutions require global cooperation. This has been a contentious debate in international discussions since the Kyoto Protocol in 1992. The economic threat from climate change often is not as recognizable as the threats that have galvanized international support for action (e.g., the Montreal Protocol to protect the stratospheric ozone layer). The fact that climate change is both external to markets and requires global cooperation is the central hurdle that policymakers must overcome if they are to slow the pace and avoid the dangers of climate change.

Providing a sense of the magnitude of impacts, an insurance industry report suggested that economic damages associated with climate change could reduce global GDP by up to 14 percent by the year 2050 (Swiss Re Institute 2021). That percentage reduction reflects damages of up to $23 trillion per year. Furthermore, many of the damages are irreversible—Earth's climate is likely to change for up to 1000 years after emissions stop due to the nature of the interaction of GHGs and the atmosphere. This suggests that some increases in temperature, aridity, and sea levels have been unavoidable since the beginning of the industrial revolution. Those effects are likely to continue further into the future the longer humans continue emitting GHGs, casting a long shadow on people and natural systems. The problem of intergeneration equity can best be described as the consequences for future generations of harm done by the current generation. Climate change experts have cited myopia, or short-term thinking, as a barrier to action on climate policy. Fundamentally, humans are an impatient species: we would rather benefit from something now and

pay for it later. This innate tendency slows progress on climate policies when the effects are not yet fully visible. It takes considerable political will to advocate for taking costly action now that will result in an uncertain amount of benefits for future generations.

Climate change requires individuals and governments to make long-term decisions with incomplete knowledge about future impacts. Knowledge of the climate system is incomplete, and future projections have uncertainties that complicate measurement of economic impacts. Economic analysis can contribute to identifying and reducing such uncertainties and informing public policy on climate change even when knowledge of how risks may play out is incomplete, but many uncertainties are likely to persist. The primary sources of uncertainty include future emissions trajectories, future changes in societal preferences, modeling limitations, measurement errors, and feedback loops. Uncertainty can affect a policymaker's degree of confidence about possible outcomes of specific decisions. Uncertainty works in both directions: the effects of climate change could be less severe than currently estimated, but could also be much more severe. Economist Marty Weitzman long argued that it is important to incorporate uncertainty and the potential for low-probability but high-impact climate events into economic and policy decisions about mitigating climate change (e.g., Weitzman 2009). The concept of irreversibility also creates its own uncertainties. On the one hand, there are well-acknowledged tipping points in the climate system (e.g., rapid melting of the Greenland ice sheet; Figure 2) that generate additional incentives to policymakers to mitigate GHG emissions now to avoid potentially catastrophic impacts. On the other hand, investments from policy actions that are not easily reversible, such as shifting economies away from fossil fuels to renewable technologies, may create a value to waiting for more information before making extensive changes. These two forms of irreversibility compound uncertainty-related issues in crafting effective climate policy (Pindyck 2021).

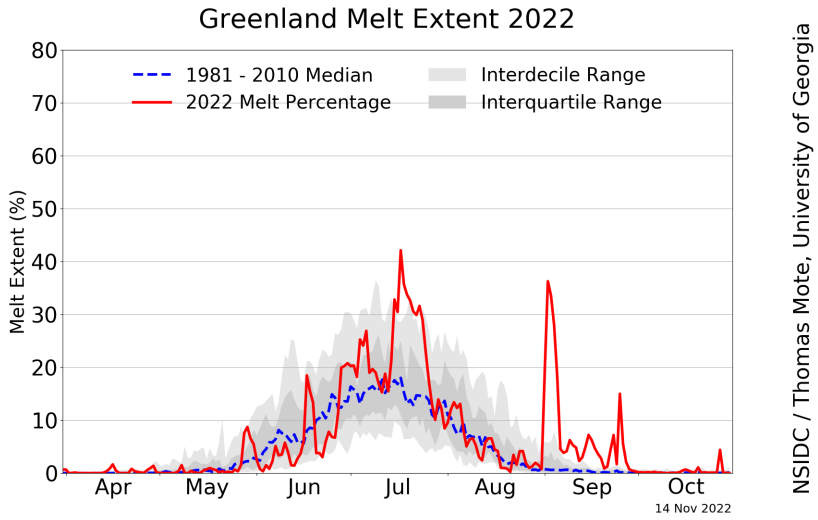

Figure 2. Recent and longer-term melting of the Greenland Ice Sheet. Source: National Snow & Ice Data Center.

The impacts of climate change vary across geographic location and social and economic status. For example, climate change is predicted to continue having a larger impact on the poorest, most vulnerable people, and there is evidence that climate change has already increased economic inequality among countries by about 25 percent (Diffenbaugh and Burke 2019). The poorest countries (and poor areas of high-income countries) are facing the worst effects of climate change, yet they are least responsible. In a system where global natural resources are shared, people often prioritize their self-interest instead of the common good, which disadvantages marginalized groups.

In the United States, there is some good news. According to the World Resources Institute, between 2005 and 2017, 41 states reduced GHG emissions while increasing their economic output (GDP),

suggesting a decoupling of economies and fossil fuel use (Saha and Jaeger 2020). Oregon was one of the 41 states that achieved decoupling, although it ranks near the bottom of the list in terms of GHG reductions (6 percent, compared to top-ranked Maryland at 38 percent).

Assessing the Economic Impacts of Climate Change

Economic impacts from recent climate-related extremes reveal substantial vulnerability and exposure of human and natural systems to climate variability. These impacts have economic consequences across a range of goods and services, such as food production and water supply, housing and transportation, and human health and mortality. For example, the Fourth National Climate Assessment suggested that climate change could reduce GDP in the United States by up to 10 percent by the year 2100 (Reidmiller et al. 2018).

Understanding the magnitude of the economic and ecological impacts of climate change is critical because most policies that can be used to reduce emissions and impacts are costly. For example, funding is needed to research and develop new technologies to make homes and other buildings more energy efficient. Market-based approaches, such as a carbon tax, would increase the cost of goods and services produced with methods that contribute significantly to climate change. An effective climate policy design would have to account not only for the economic costs that arise from policy implementation, but also for the benefits of mitigating future impacts of climate change. Estimating these impacts, and therefore the potential benefits of taking action now, is difficult. There are uncertainties in emissions trajectories, climate model outputs, and human behavior in response to policy changes. Estimation of impacts often is based on models that include sets of assumptions about the range of potential outcomes and how systems will respond to change. Hence, as recent research has shown, global economic impacts of climate change are often hard to identify and estimate because these efforts have covered a variety of economic sectors and relied on different foundational assumptions, such as the discount rate and responses to catastrophic changes.

An additional key challenge in estimating economic damages from climate change is understanding the causal links among elements of the climate system and society. Attribution of climate impacts must be separated from the impacts of day-to-day weather while accounting for humans' adaptive capacity. As explained in the fifth Oregon Climate Assessment, attribution of climate phenomena is "the process of evaluating the relative contributions of multiple causal factors to a change or event with formal assessment of confidence." For example, it was estimated that the intensity of precipitation during Hurricane Harvey, which generated extreme flooding in Texas in 2017, was 20 to 40 percent greater due to climate change (Risser and Wehner 2017). Attribution more commonly is applied to estimate changes in the likelihood of an event or class of events because of human activities than to gauge whether climate change caused a certain event.

Improving attribution can support estimation of the quantity of damage from climate change, but prices also are needed to value economic impacts of climate change. An important economic price in this context is the social cost of carbon (SCC). The SCC is an estimate, in dollars, of the economic damages that would result from a marginal change in emissions (an additional ton of GHGs) and its consequent effects on climate change, society, and ecosystem function. The impacts are estimated in dollars to help policymakers understand the outcomes of decisions that would increase or decrease emissions. The SCC is used by local, state, and federal governments in the United States and other countries to inform billions of dollars of policy and investment decisions. The SCC in the United States is around $185 per ton of carbon dioxide (Rennert et al. 2022).

Valuation of market impacts can translate climate to physical changes in economic output and then use market prices, or the SCC, to estimate damages. However, there is no market for important features of society and the natural world, such as ecosystem services, wildlife species, and human well-being and health (Figure 3), and these are often not included in SCC estimates. Although these items are not bought and sold in a manner that can reveal an economic price, they have economic value and warrant consideration when estimating impacts from climate change. Three primary sources of nonmarket economic value are likely to be affected by climate change. The first, use value, is the utility or benefit an individual receives from consuming a good or using a service. The second, option value, is a value that is placed on maintaining the environment or a particular resource so an individual has the option of enjoying it in the future even if they currently do not use it. The third, nonuse value, is the value that people assign to goods even if they never have and never will use the good. Examples include existence values, where people receive benefits from knowing that a particular resource exists (e.g., an endangered species), and bequest values, where benefits arise from preserving the availability of a resource to future generations.

Figure 3. There is no market for many features of the natural world. Photograph by Erica Fleishman.

Although many tools exist to estimate nonmarket values, the magnitude of economic loss from nonmarket environmental damage remains difficult to assess at scales relevant for integration into global climate policy discussions.

Climate Policy Options: Economic Efficiency Versus Political Feasibility

There are two primary policy avenues to address the economic effects of climate change: mitigation and adaptation. Mitigating the effects of climate change requires actions to limit the magnitude and rate of change, typically through reducing emissions of GHGs. Climate mitigation often focuses on reducing the use of fossil fuels by limiting energy production from fossil fuels, switching to low carbon fuels or renewable energy production, or increasing systems' energy efficiency. Damages can also be mitigated by enhancing the capacity of carbon sinks by preserving or restoring natural ecosystems, such as forests, or inventing new carbon-capture technologies. Adaptation involves practical and realistic actions to manage risks from climate change, protecting and strengthening communities, and improving resilience of the economy to future effects of climate change.

The primary goal of mitigation policies is to stabilize GHG levels in a time frame sufficient to allow humans and ecosystems to adapt naturally to climate change, to ensure, for example, that agricultural

systems can maintain levels of production to prevent food shortages. The three general policy strategies to mitigate GHG emissions are market-based approaches, regulatory approaches, and voluntary agreements. Economists often support market-based policy instruments such as carbon taxes or cap-and-trade (i.e., collectively determining the price of carbon) as an incentive-compatible strategy to reduce the use of fossil fuels. Carbon pricing policies function to charge the parties responsible for emissions of GHGs. These strategies are considered cost-effective for four primary reasons. First, a carbon price will minimize the societal costs of emissions reductions. Second, carbon pricing provides firms with flexibility to find the least costly way to reduce emissions. Third, carbon pricing encourages more reduction in GHG emissions than conventional regulations because it also provides an incentive to reduce demand for fossil fuels. Fourth, a price on carbon offers potential for a new revenue stream for government use to invest in renewable energy, offset distributional impacts of the pricing policy, or reduce other distortions in the economy.

Regulatory approaches include technology and emissions standards, product bans, and government investment. An example of regulatory efforts in the transportation sector is the 2020 Safer Affordable Fuel-Efficient (SAFE) vehicles rule, which seeks to increase fuel efficiency standards to reduce GHG emissions from passenger cars and light trucks (model years 2021–2026). Voluntary agreements are made between governments and private actors to achieve an environmental goal. The U.S. Environmental Protection Agency partners with the public and private sectors to oversee voluntary programs aimed at reducing GHG emissions and increasing clean energy adoption (e.g., the Energy Star program, www.energystar.gov).

The aim of adaptation policies is to reduce society's vulnerability to the harmful effects of climate change. In terms of policy options, two important questions are the timing of action and the economic agents. Adaptation can be either reactive—in response to an event or stimulus—or anticipatory, where actions are taken before impacts are observed. An example of reactive adaptation is a farmer planting a new, more drought-tolerant crop this year because of drought-related crop losses last year. An example of anticipatory adaptation is a government agency, such as the Federal Emergency Management Agency, providing funding to homeowners in a floodplain to elevate their homes now to avoid potential future flood damages. Adaptation actions can be taken by different entities. Private adaptation is a behavioral response by one individual for their own benefit. For example, an individual in Oregon might install air conditioning in their home in response to higher temperatures. Joint or public adaptation actions benefit many individuals simultaneously. For example, in Florida and other states, the U.S. Army Corps of Engineers adds sediment to widen beaches with the goal of creating a buffer to protect homes and infrastructure from storms.

Some policy options can achieve both mitigation and adaptation objectives. For example, coastal wetlands are a carbon sink, and restoration could enhance their capacity to capture and store GHGs. Wetlands also can absorb water from storm surges and protect infrastructure and homes nearby, providing a public, anticipatory adaptation to climate change. A recent coastal restoration project in Oregon suggested that a single policy intervention can meet both mitigation and adaptation objectives while also providing economic benefits at state and local levels (Shaw and Dundas 2021).

Sector-Specific Economic Impacts in Oregon

Agriculture

The breadth and economic importance of Oregon's agricultural sector is reflected in summary statistics derived from the U.S. Agricultural Census (Sorte et al. 2021). In 2017, the total value

of Oregon's agriculture, food, and fiber industry was approximately $42 billion, with farm gate production accounting for $5.5 billion. Almost seven percent of Oregon's jobs directly depended on the agricultural sector. Sixteen million acres in Oregon (60 percent of private land) were dedicated to farming, and over 225 agricultural commodities were produced in the state. This diversity is an economic strength but makes it challenging to draw generalizable themes about the impacts of climate change on Oregon's agricultural sector.

Research on agriculture's role and opportunity in climate policy for mitigating GHG emissions began in earnest more than 30 years ago. A robust body of research has provided measures of the impacts of climate change on agricultural productivity and net returns, and identified policies and programs that could reduce the rate of emissions from agricultural sectors and contribute to net-negative carbon emission goals (Paustian et al. 2006). Technologies and innovations to reduce emissions will only be effective if they are adopted by agriculture and food sector stakeholders, so site-specific research is needed on the economic feasibility and long-term sustainability of proposed climate policies and related changes to production practices and processes.

Several factors limit the impacts of mitigation efforts. One is additionality. The goal of climate policy should be reductions in GHGs above and beyond those that farmers or other stakeholders, including forest owners, would make absent the climate policy. Another issue is permanence. Some changes in agricultural management, notably the sequestration of carbon in soils through photosynthesis and root growth, and incorporation of organic matter into the soil, can be reversed through disruption of the soil by tillage (see *Regenerative Agriculture*, this volume). While the lack of permanence in farm-related carbon sequestration programs has been a long-standing concern, there is some value to creating incentives for temporary carbon sequestration policies to provide more time for permanent solutions to be adopted (Antle et al. 2003). A third issue is leakage or slippage. A policy of encouraging planting and maintaining trees rather than harvesting can raise the price of wood elsewhere and cause more harvesting, thus offsetting the global benefits of the policy. Similarly, conservation policies in a large country such as the United States—for example, the Conservation Reserve Program, in which farmers receive an annual payment to remove erosion-prone land from agricultural production and plant species that will improve environmental quality—can increase the area cultivated elsewhere, releasing carbon stored in soils.

Reliance on voluntary action by consumers or farmers is unlikely to realize the full potential for agriculture to contribute to mitigation because reducing emissions, changing production practices or crops, and sequestering carbon usually is costly to farmers. For example, adoption of precision management technology, such as variable-rate seed and fertilizer applications enabled by machinery equipped with global positioning systems, varies across the United States and is not necessarily economically superior to conventional, uniform management (Basso and Antle 2020). Agrivoltaic farming—co-locating increases in agricultural productivity and generation of renewable energy—is a counter-example of an innovative, voluntary action that may have net gains (Box 1).

Farm-scale decision tools or software enable growers and researchers to better understand the economics of climate trends or changes in site-specific production practices, and provide insights and information on options to modify production practices (Capalbo et al. 2017). Decision-support tools that link with research on climate change and productivity and allow agricultural managers to better understand novel options and opportunities are fundamental to translating research to outcomes. AgBiz Logic™, the Profitability Decision Tool, and the Tradeoff Analysis Project exemplify recent decision tools that are incorporating climate change impacts.

AgBiz Logic™ provides economic, financial, and environmental decision tools for assessing alternative technologies and innovative processes. For instance, the tool has been used to incorporate projected climate changes in farm-based decision planning by apple growers in Washington (Box 2).

The Profitability Decision Tool (www.pnwlit.org/profitability-decision-tool) assists exploration of alternative rotations in dryland farming systems of the inland Pacific Northwest. Alternative cropping rotations can provide feasible options as springs become wetter and summers become drier and hotter. The tool can be used to compare the economic and financial impacts of changing to an alternative crop rotation.

Box 1. Agrivoltaic Farming

Food production and climate change impacts are typically framed in a negative context. The emphasis is often on issues such as changes in growing conditions, frequency and severity of harmful weather events, and a general deterioration in production capacity. Positive contexts, however, also exist, particularly with respect to technological innovations spurred on by anticipated needs to mitigate negative climate change impacts. An example is ongoing development of agrivoltaic farming. The goal of this technology is to combine production of solar energy and food on the same plot of land. "The hallmark characteristic of agrivoltaics is the sharing of sunlight between the two energy conversion systems: photovoltaics and photosynthesis. It essentially mimics what humans have been doing for hundreds of years with agroforestry—think shade-grown coffee—intentionally creating partial shade to create multiple layers of agricultural productivity on the same piece of land" (Macknich as quoted by Gordon 2022). Numerous approaches to agrivoltaic farming are being researched and developed (Figure B1), including placement of solar panels on dry, unirrigated farmland to increase crop yields via reduction of water use and heat stress on plants and grazing animals (Adeh et al. 2019).

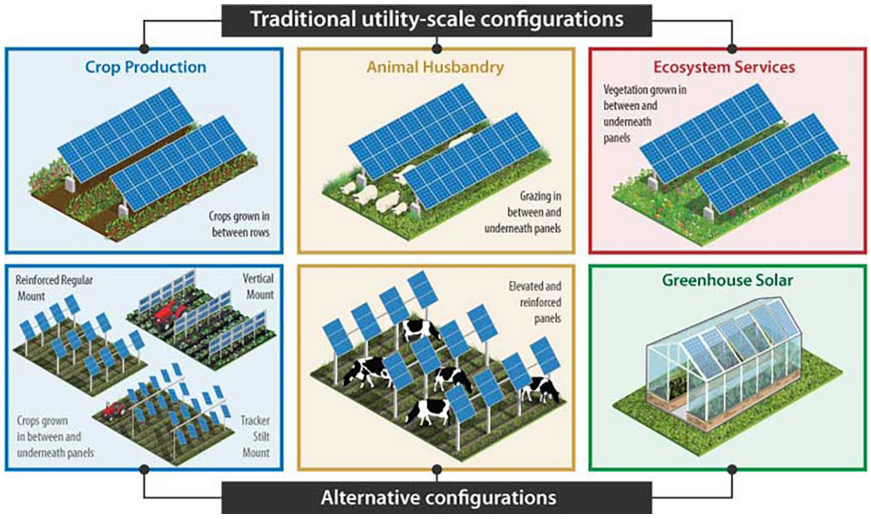

Figure B1. Agrivoltaic systems can be installed in the same basic row layout as a traditional large-scale solar plant. Alternatively, they can be modified to provide extra space for light, animals, or farm equipment to move under and among them. Source: Dreves 2022.

The Tradeoff Analysis Project (agsci.oregonstate.edu/tradeoff-analysis-project) develops modeling tools that can be used to improve understanding of agricultural system sustainability and inform policy decisions. The software is based on the whole farm system (crops, livestock, aquaculture, non-farm income) and simulates economic indicators (per-capita income, income-based poverty) and mean and threshold indicators for economic, environmental, or social outcomes associated with the systems. An application of this tool examines impacts of climate change on the winter wheat sector in the Pacific Northwest and indicates higher yields on average from future climate scenarios, although there are both winners and losers due to variations in weather and biophysical and socioeconomic conditions. (www.reacchpna.org/sites/default/files/tagged_docs/6c.2.pdf).

Specialty fruit crops represent a substantial portion of the value of agricultural production in the Pacific Northwest. Climate change will most likely threaten water sources, lengthen the dry season, raise temperatures during both the winter chilling period and the growing season, and facilitate the

Box 2. Incorporating climate impacts in farm-based decision tools

Van Name et al. (2017) discussed the use of AgBiz Logic™, a decision tool that measures the economic effects of climate change, and illustrated the use of this tool with apple production in the Pacific Northwest. In 2015, snowpack levels in the Pacific Northwest were the lowest on record. Snowpack levels strongly affect the volume of water available for irrigation by those with water rights in the area. Most irrigation replenishes water lost through evapotranspiration, but irrigation also is used to cool crops in hot weather. AgBizClimate, part of the AgBiz Logic™ suite of economic, financial, and environmental decision tools for agricultural businesses (Seavert 2015), was used to inform growers about impacts due to low snowpack. Still in development, AgBizClimate is an online application that delivers essential information about climate change to farmers and land managers, including relevant climate variables modeled into the 2040s.

Van Name et al. (2017) surveyed growers with the goal of obtaining insight into the types of weather that have the greatest effects on crop yields. Apple growers based in Yakima and Wenatchee, Washington, indicated that they most frequently monitored snowpack, accumulated growing degree days, the number of consecutive extremely hot days, and the number of nights below freezing (Table B1).

Variable thresholds and comments
Number of days above freezing • Determines the developmental stage of the fruit
Number of nights below freezing • Winter injury to fruit trees from November through March, spring frost from March through May • Overnight low temperatures in spring can freeze fruit buds • Contributes to cost of frost protection to save fruit buds
Number of consecutive extremely cold days • Three or more days of temperatures below 0°F (-18°C) can cause winter injury to fruit trees
Number of consecutive extremely hot days • Three or more days above 95°F (35°C) can cause sunburn on fruit skins
Accumulated growing degree days • Drives models of pests (especially codling moth [*Cydia pomonella*]) from April through August. Pests can increase chemical costs and the number of chemical applications.
Accumulated chilling hours • Certain apple varieties require more than 400 chilling hours to avoid blush coloring on the skin of the fruit
Snowpack • Amount of snowpack is 100% of the seasonal supply to all water rights holders in the Yakima River basin • Affects the severity of drought, which affects and limits irrigation and overhead cooling strategies

Table B1. Examples of grower-defined thresholds.

see **Agriculture**, page 144

spread of fungal diseases and insects. Such changes have the potential to substantially reduce net returns due to increased input costs and altered yields and product quality. Houston et al. (2018) highlight changes in climate and key vulnerabilities that are already influencing specialty fruit crop production in the Northwest and identify adaptation strategies and actions that improve both yields and quality of crops and retain the economic viability of specialty fruit crops in the region. Many management strategies that are already being used to prolong growing seasons in marginal production areas and to improve production and quality in established production regions may also be useful as adaptation strategies under a changing climate. These near-term strategies involve moderating temperatures through use of overhead sprinklers and shade netting or compensating for mismatches between phenology and seasonal weather conditions. Longer-term strategies include investment in new varieties.

Climate change also appears to be impacting the frequency and severity of wildfires. The 2020 wildfires in Oregon significantly impacted the agriculture, food, and fiber sector (Sorte et al. 2021). Concerns and damages ranged from the taste of the food produced from the tainted crops to the crops absorbing toxicants in the smoke. The Oregon Wine Board estimated approximately a 20 percent decline in industry revenues in the 2020 crop year (Sorte et al. 2021). In Oregon, wine growers are experimenting with alternative varietals. One grower reported that their estate had worked with 28 different varietals in 2019, in part as a "way to be ahead of a changing climate" (Gruber 2020). Both growers and wineries are developing integrated risk management strategies to deal with the ever-increasing likelihood of droughts and wildfires. A

Agriculture, from page 143

To use AgBizClimate, the grower selects previously generated enterprise budgets from AgBiz Logic™ that best reflect their personal economic situation, whether grower data or representative returns and costs from readily available university budgets. These budgets serve as a baseline for estimating subsequent climate impacts. Modifying the base budget (e.g., for Gala apples, Figure B2) for alternative climate and productivity or cost assumptions decreased net returns. In all four scenarios, climate change substantially reduced the net returns per acre, indicating that higher losses of packed fruit sold to the fresh market resulted in a greater loss to net returns than additional chemical costs and application rates.

The AgBiz Logic™ results for apple production illustrate that changes in climate will have a large effect on current agricultural practices and overall net returns in Pacific Northwest apple orchards. With no changes in management practices, apples in the Pacific Northwest will on average fare better during winter due to decreases in winter injuries to trees. Apples will fare worse during summer as the increased frequency of consecutive extremely hot days and accumulated growing degree days affects fruit quality and insect pressures. The downscaled information from AgBizClimate on projected changes in yield and production inputs are the impetus for producer-generated adjustments in input use, management, and technology adoption that may alleviate the negative impacts or take advantage of adaptation opportunities.

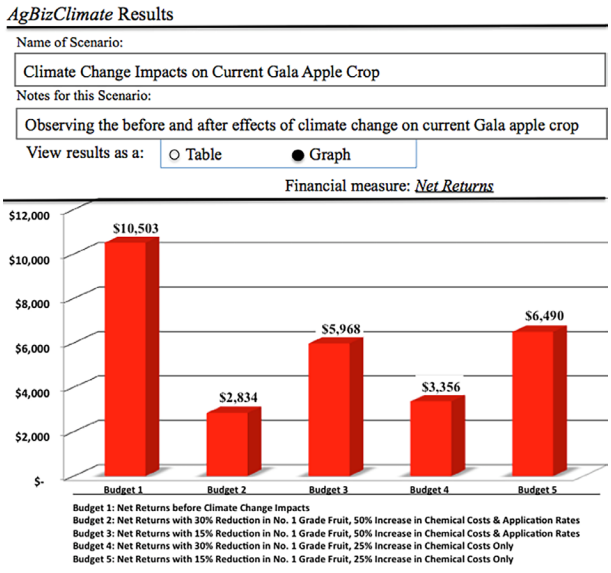

Figure B2. Example AgBizLogic™ results for Gala apples.

group of researchers in the western United States have launched a multi-state, multi-year project to develop best practices in response to drier, more extreme weather and smoke events (Box 3).

Similarly, wildfires in northern California adversely impact wine grape growers and wineries directly, via destruction of property (vineyards and facilities), and indirectly, by making the grapes unsuitable for wine production (Kropp and De Andrade 2022). In 2020, over $600 million of wine grapes went unharvested. Wildfires have resulted in changes in contracts among growers and wineries and changes in purchasing of crop insurance policies to mitigate direct and indirect risks to this sector. A record number of grapes under contract were rejected in 2020, representing nearly a 20 percent decline in tons of crushed grapes relative to 2018 (Kropp and De Andrade 2022).

Climate change also has the potential to significantly affect irrigation practices and the availability and use of scarce water in Oregon. Bigelow and Zhang (2018) provided a direct assessment of climate adaptation through the lens of agricultural irrigators in Oregon. The findings highlighted how agricultural producers in Oregon have already adapted to changing climate by acquiring supplemental irrigation rights, which allows producers to diversify their irrigation water sources. Supplemental water rights give irrigators access to another source of water if they cannot withdraw the full amount of water granted to them through the primary water right from the primary source (e.g., if junior surface water users are regulated off in a given basin, a supplemental groundwater right could be used to make up the shortfall). Olen et al. (2016) highlighted how three primary aspects of irrigation decision-making (share of farm irrigated, irrigation water application rate, and technology adoption) change with climate conditions and drought across various production specialties. The general findings suggested that temperature is a more important driver of these choices than precipitation. The study went on to highlight how these

decisions are altered when the motivation for irrigation is to mitigate damage resulting from heat versus frost.

Research on water scarcity in the Willamette River basin and policies to mitigate and adapt to changes in water scarcity due to climate change have focused on changes in the availability of water that are priced and exchanged in markets (e.g., urban water) and changes in the values of resources not exchanged in markets (e.g., instream flows, forest health, flood risk protection, recreational opportunities) (Jaeger et al. 2017, 2019). This research projected trajectories of change on the basis of interactions between biophysical and human processes and is used as a tool to describe a range of future conditions associated with climate and water scarcity scenarios. The project indicated that a decline in snowpack in the next 80 years will reduce the amount of snowmelt runoff by 600,000 acre-feet of stored water. Reduced snowpack, when combined with higher summer temperatures, will increase stress on upland vegetation and increase the risk of wildfires. Furthermore, precipitation will have a far greater role than snowmelt in determining spring stream flows in the Willamette River basin. The project found that climate change is projected to result in earlier crop planting, which will lead to more crop growth during the months when temperatures are cooler and soil moisture is greater. Earlier planting will also lead to an earlier start, and completion, of irrigation. Moreover, the potential use of stored water to expand irrigation to farmlands that currently do not have irrigation water rights is limited by economic realities; conveyance costs are high relative to the economic gain from irrigating. Also, the project concluded that thirteen federal storage reservoirs in the Willamette River basin reduce the risk of flooding. This benefit has been estimated to be more than $1 billion per year. As urban areas expand and climate change leads to increases in the frequency and magnitude of high flows, the value of potential damages associated with flood events will rise.

Box 3. Research on threats of wildfire smoke to the wine industry

For the West Coast wine industry, the 2020 growing season left an enduring and unsettling memory. Large wildfires that burned across California, Oregon, and Washington destroyed some wineries and vineyards. Moreover, smoke circulated and settled into some vineyards for an extended period. Persistent exposure to smoke compromises the quality and value of wine grapes and adversely affects wines. The estimated financial loss of $3.7 billion will extend into 2023 because many wineries decided to not produce wine from grapes grown in 2020, and winery sales lag for more than one growing season because wines are aged and stored before sale (Adams 2021).

Image by Jill Wellington from Pixabay.

A team of researchers from Oregon State University, Washington State University, and University of California, Davis, supported by a $7.5 million grant from the U.S. Department of Agriculture, is collaborating to better understand how smoke density and composition affect grapes, grape vines, wine composition, and sensory perception of wine in a glass. They also aim to provide decision-support tools and guidelines to assist the grape and wine industries during future smoke events.

Reimer et al (2020) used a multi-sector economic simulation tool to estimate the overall robustness and resilience of the Hermiston economy to environmental shocks due to a changing climate. Regions with vulnerabilities in their food-energy-water nexus are likely to have economic vulnerabilities, and steps to address any environmental vulnerabilities (such as increasing water

scarcity as a result of climate change) may conflict with regional and county-level concerns about employment and overall economic health as measured in terms of current and near-term economic vitality. The Hermiston area's water is allocated to different uses, such as electricity generation, farmland irrigation, municipal water, fisheries, and data center cooling. The multi-sector simulation model predicted that a one percent increase in surface water availability would lead to a $1.05 million increase in the size of the Hermiston economy, which translates into a little less than one percent.

A few takeaway messages for assessing the economic impacts of changes in climate, water availability, and resilience of local economies with a multi-sector simulation tool are as follows. First, it is important that economic models account for availability of key ecosystem services and levels of natural resources, and likewise that engineering models include behavioral information on how economic decision-makers reallocate resources under scarcity scenarios. Additionally, when a simulation tool provides information on the overall robustness and resilience of a local or regional economy to changes in water availability or other environmental shocks due to a changing climate, the tool also can provide further information on the benefits and costs to the local economy of actions to enhance other environmental outcomes such as ecological restoration, recreation, or wildfire mitigation.

Forests

Nearly 47 percent of Oregon is forested, and forestry contributes ~2.1 percent to the state's GDP. Annual timber harvests average ~3.8 billion board feet, and the industry supports around 3 percent of jobs (~62,000) in the state (OFRI 2022). Oregon is the leading U.S. producer of softwood lumber, plywood, and value-added engineered wood products. Early economic work on the impacts of climate change on forests in the United States suggested that timber stocks may expand and market benefits are possible (Sohngen and Mendelsohn 1998). The state's forests also support outdoor recreation, provide habitat for endangered species, and protect water supplies.

Forests can mitigate climate change by acting as carbon sinks, absorbing GHGs from the atmosphere and storing them in biomass and soils. When cleared, degraded, or burned, they can become sources of GHG emissions. In Oregon, forests act as a carbon sink, removing nearly 31 million metric tons of carbon dioxide from the atmosphere each year (Christensen et al. 2019). This estimate accounts for GHG absorption by live tree growth, net emissions from harvesting, and mortality events (including wildfire). The economic value of this ecosystem service, assuming $185 per metric ton as the social cost of carbon (Rennert et al. 2022), translates to a benefit of over $5.7 billion per year. This economically significant service suggests that forest management plays a crucial role in climate policy.

Although nearly 62 percent of forest carbon-storage capacity in Oregon is from national forests (Christensen et al. 2019), private timberland management also plays a role. Net carbon flux from forest management can be impacted by decisions on both the intensive (i.e., choices such as rotation length and thinning) and extensive (i.e., changes in size of forest or forest type) margins. A vast literature on the topic suggests that incentives (e.g., subsidies or taxes) could induce landowners to sequester carbon by planting or maintaining trees as a cost-effective means to meet policy goals (e.g., Lubowski et al. 2006), although consensus on the best approach has not been reached (Li et al. 2022). In fact, a carbon tax may lead to net emissions and loss of forest, suggesting that the climate policy tools applicable to land use may be different than those applicable to other regulated sectors of the economy (Li et al. 2022).

Box 4. Switching from Douglas-fir to ponderosa pine

Climate change may bring significant changes to private timberland in Oregon and the western United States (Hashida and Lewis 2019). Author David Lewis said, "About half of all non-federal forestland that is harvested in Oregon and Washington is currently replanted with Douglas-fir by landowners. But Douglas-fir will be less productive in a warming climate. The tree's ability to sequester carbon will diminish and landowners are more likely to switch to other trees." The proportion of land planted with Douglas-fir may decline to 25 percent by 2100 as landowners change their planting decisions in response to climate change (Hashida and Lewis 2019).

Hashida and Lewis (2019) also explored the impact of a policy that would pay landowners to delay or forgo harvest in order to sequester carbon. Current policy examples of carbon sequestration in forests include the use of carbon offsets in California's cap-and-trade program for carbon, which was a model for a program in Oregon that was proposed but not passed by the legislature. Such a carbon pricing policy would accelerate the transition from planting Douglas-fir to planting hardwoods and ponderosa pine. This policy, combined with landowner adaptation decisions, would further reduce the proportion of land planted with Douglas-fir to 15 percent (Figure B3).

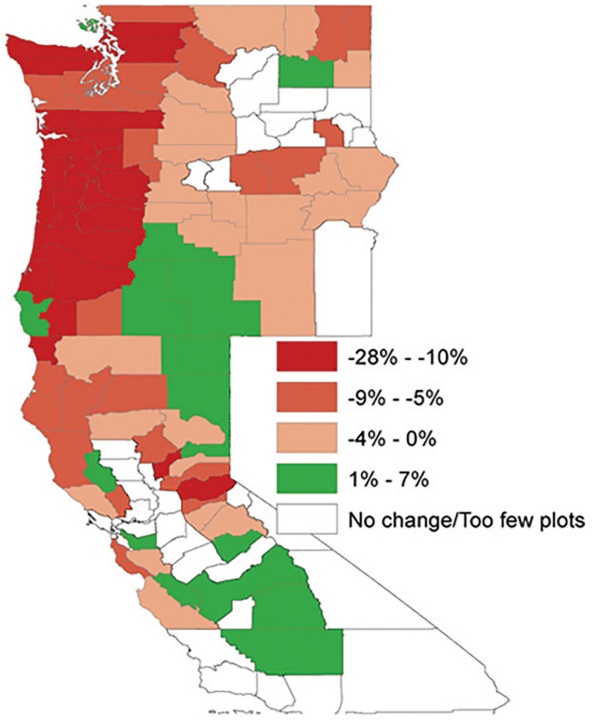

Figure B3. Effects of climate change and carbon pricing on Douglas-fir planting. Source: Hashida and Lewis 2019.

Climate change also has the potential to change the compositions of Oregon's forests. It is estimated to be a contributing factor to reducing the productivity of Douglas-fir (*Pseudotsuga menziesii*) across western states (Crookston et al. 2010, Restaino et al. 2016, Weiskittel et al. 2012) and reducing post-fire viability of Douglas-fir (Davis et al. 2020). A warmer and drier climate is projected to induce a gradual shift by private landowners in Oregon away from Douglas-fir, the state's currently most valuable tree species, toward hardwood species (Hashida and Lewis 2019; Box 4). An economic model estimated that climate change will induce a loss of private timberland value of 39 percent by the year 2050 in western Oregon and Washington (Hashida and Lewis 2022). The results of these economic studies are also consistent with a recent simulation that suggested climate change and increased wildfire activity will drive a shift from coniferous forests to shrubland-hardwood forests in the Klamath region (Serra-Diaz 2018).

Furthermore, recent modeling efforts demonstrated that there are likely to be additional trade-offs associated with a transition from Douglas-fir to other trees. For example, the projected total loss of habitat for 35 species of amphibians, birds, and mammals of conservation concern in the western states exceeded the total area of habitat gained, and the net loss of habitat accelerated over time as climate changed (Hashida et al. 2020). Accordingly, adaptations by private landowners to climate change can induce social costs to non-landowners (Hashida et al. 2020).

Oceans and Coasts

Oregon's coastline stretches over 575 km (360 mi) from the California border to the Columbia River. The coastal zone is home to 225,000 people, less than 7

percent of the state's population, but supports vibrant tourism and fishing industries. According to Travel Oregon (2022), tourism in Oregon generates $5.4 billion (~2 percent of state GDP) annually. Tourism along the Oregon coast supports nearly 253,000 jobs and $1.93 billion in visitor spending each year, with a significant increase over the last decade (Travel Oregon 2022). Commercial fisheries in the state also generate substantial revenue and employment. In 2019, commercial landings generated nearly $560 million in statewide income and supported 9200 jobs (The Research Group 2021). Dungeness crab is the most valuable commercial fishery in the state, representing about one-third of the economic value from the industry. Recreational fisheries also generate considerable economic returns ($120 million in income, 2000 jobs supported in 2019; The Research Group 2021).

Climate change is already affecting tourism and fishing in Oregon, and an organization representing Dungeness crab boats is suing oil and gas companies for climate damages for harmful algal blooms caused by warming ocean waters (Box 5). Dungeness crab and Pacific oysters are valuable commodities that are also susceptible to ocean acidification, which has potential to result in loss of fisheries productivity and reduced economic opportunity. Action plans at the state level aim to develop solutions to mitigate these potential economic impacts (Whitefield et al. 2021).

Oregon's oceans and coasts are also an area for harnessing wave and offshore wind energy in an effort to expand capacity for renewable energy production. The U.S. Department of Energy recently funded PacWave (pacwaveenergy.org) to develop a wave energy testing facility off the coast of Lincoln County. The facility, which was granted a license by the Federal Energy Regulatory Commission to begin operations, will be the first commercial-scale grid-connected test site for wave energy. In September 2022, the Biden administration announced plans to develop floating platforms for offshore wind off the Oregon coast (Daly and McDermott 2022). The economic implications of increasing Oregon's renewable energy capacity are uncertain, but a government report suggested that offshore wind could generate up to $5.7 billion in economic activity and support 66,000 jobs during the construction phase, and billions in state GDP and thousands of employment opportunities over the long term (Jimenez et al. 2016).

Salmon in the Pacific Northwest are also susceptible to the effects of climate change. All salmon are anadromous, spawning in fresh water but maturing in oceans, and most spawn only once before dying. Pacific salmon are threatened by water diversions, dams, and logging when in their freshwater habitats. For populations to remain viable, adults must migrate to spawning habitat, and survival of the eggs and larvae requires cool water, gravel substrates, and sufficient water flow and oxygen. There also must be enough water flow to support migration back to the sea. Climate change is affecting all of these elements in ways that threaten the survival of salmon runs, and several of the region's populations may be approaching physiological temperature tolerances (Crozier et al. 2019).

Maintaining salmon populations as climate changes will require restoration of large patches of connected habitat. Residents of the Pacific Northwest place significant value on such restoration efforts for threatened Oregon Coast coho salmon populations (Lewis et al. 2019, 2022). A nonmarket valuation survey estimated that the regional willingness to pay for restoration efforts that increase coho runs by 100,000 fish approaches a half a billion dollars per year (Lewis et al. 2019). Restoration of salmon habitat in coastal and marine environments could also provide co-benefits of carbon sequestration and buffers against sea level rise and storm surges (Dundas et al. 2020).

The risk that erosion will affect coastal housing and infrastructure in Oregon is increasing due to climate change effects on winter storms, El Niño–Southern Oscillation (ENSO) events, and sea level rise. Increased erosion creates a fundamental tension between coastal property owners who want

to protect their homes and investments, often with hardened shoreline armoring such as sea walls or rip-rap revetments, and the public right to recreate on the coast as codified by the 1967 Beach Bill. Recent research examined the economic value to coastal housing markets generated by state land-use regulations that limit armoring (Dundas and Lewis 2020). Homes in areas with the option of hardening the shoreline for erosion protection sold for 13 to 22 percent more than similar homes without the option of protection. Additionally, the right to armor may impose costs on neighbors that are not eligible to armor, reducing their land value by nearly 8 percent. Landowners' decisions about whether to armor their shoreline are highly influenced by the observed actions of neighbors (Beasley and Dundas 2021). Scenario-based simulations suggested that private armoring along the Oregon coast would increase 70 percent if Goal 18 land use regulations (www.oregon.gov/lcd/OP/Pages/Goal-18.aspx) were removed. Currently, Goal 18 limits private shoreline armoring to properties that existed prior to 1 January, 1977, when the armoring prohibition went into effect. Coastal land-use policy generates value and loss, and may be a key factor in how the Oregon coast adapts to climate change.

Box 5. Oregon's Dungeness crab fishery sues 30 fossil fuel companies

An extensive area of unusually warm water in the northern Pacific Ocean in the mid-2010s, known colloquially as The Blob, led to a surge in toxic algae. These events led to an increase in domoic acid, a neurotoxin that cost the West Coast Dungeness crab fishery more than $150 million in 2015. This disruption, and other season delays in subsequent years, led to many boats moving to different fisheries or going out of business. In 2018, the Pacific Coast Federation of Fishermen's Associations, which represents commercial harvesters and onshore processors and wholesalers, decided climate change was the culprit and initiated a lawsuit against fossil fuel companies for actively covering up their role in climate change. The lawsuit also sought damages for anglers impacted by these events. This was the first time a private organization attempted to sue the oil and gas industry for climate damages. As of November 2022, the legal case is ongoing.

Image by Sabrina Eickhoff from Pixabay

Other Important Economic Impacts

Public Health

Nationwide, the impact of climate change on public health, including mental health, is receiving serious attention. Oregon Health Authority (OHA) provided two reports, one each in 2014 and 2020 (OHA 2014, 2020). The message of the 2020 report is clear: climate change is a public health threat disproportionately affecting lower income communities, communities of color, tribal communities and frontline workers. " . . . agricultural workers, fishers, forestry workers and hunters account for 20 percent of heat-related deaths in the United States . . . In urban areas, people who work and reside in urban heat islands (i.e., construction workers) are also more at risk of climate-related health hazards" (York et al. 2020:39). The report notes that lower income and rural Oregonians have a harder time adapting to climate change because they have fewer options available to them and less financial stability. They also tend to work in jobs that are outside or on the front lines and live in hotter areas that will be more vulnerable to climate-related food and housing insecurity. Additionally, recent

research suggests that rates of traumatic injuries for outdoor workers (e.g., heat stroke, dehydration) are significantly higher during hotter weather, especially for agricultural workers (Evoy et al. 2022).

In recent summers, Oregonians have experienced unprecedented wildfires and record setting heat waves. These heat waves bring an increase of heat-related hospitalizations and respiratory illnesses, in addition to increased water insecurity, ozone pollution, airborne pollutants, molds, and allergens in the air. The OHA 2020 report notes, "if greenhouse gas emissions remain high, most of the state will experience significantly more days with temperatures above 86°F . . . by the year 2040." This projection was borne out in record-setting heat waves from June through August of 2021 and 2022. The Oregon Environmental Council (OEC) summarized the OHA 2020 report, noting estimates of the health costs of climate change on selected health outcomes (heart disease, stroke, asthma and premature births) at nearly $10 billion per year (oeconline.org/oha-report-climate-crisis-a-current-and-growing-threat-to-the-health-of-oregonians).

Increasing frequency of wildfires also produces public health concerns for Oregon. Dittrich and McCallum (2020) provide a review of the health impacts of wildfire smoke and economic approaches to estimate damages, with a focus on the Pacific Northwest. Their findings suggest costs could be in the billions of dollars, driven mostly by increases in premature mortality related to smoke exposure. Fine particulate matter ($PM_{2.5}$) in wildfire smoke can increase the incidence of violent crime (Burkhardt et al. 2019), worsen health outcomes (Bishop et al. 2018, Deryugina et al. 2019), and reduce labor productivity (Graff Ziven and Neidell 2012). Furthermore, current government policies that rely on individuals to protect themselves from wildfire smoke, such as by staying inside or buying air filters, are likely to have minimal benefits that are likely to be unequally distributed across household-based income (Burke et al. 2022).

Recreation

Outdoor recreation contributed 1.8 percent (~$375 billion dollars) to U.S. GDP in 2020 (Bureau of Economic Analysis 2021). The contribution of outdoor recreation to Oregon's state GDP (2.2 percent) is higher than the national average. In Oregon, outdoor recreation supported 224,000 full-time jobs and $15.6 billion in spending in 2019 (Mojica et al. 2021).

Recent empirical research suggests that climate change is likely to affect many forms of outdoor recreation and that impacts are likely to vary across seasons, locations, and activities. Increases in the incidence of days with extreme heat are likely to have negative economic effects on marine recreational fishing, but the magnitude of the impact will depend on the adaptability of recreators to adjust the timing of fishing (Dundas and von Haefen 2020). By contrast, climate change may improve economic welfare for the cycling sector by expanding recreation windows in spring and autumn (Wichman and Chan 2020). Recent research suggests some Oregon-specific impacts of climate change on winter recreation. Peak annual snowpack in the Oregon Cascade Range may decline by 25 percent by 2050 and 75 percent by 2100 (Siirila-Woodburn et al. 2021). Reduced snowpack in the Oregon Cascade Range may result in nearly $19 million annually in total damages to activities related to skiing, and damages are projected to $425 million per year in California (Parthum and Christensen 2022).

Wildfires also are likely to have substantial negative impacts on outdoor recreation. Not only do wildfires create smoke, which may limit many types of outdoor recreation across a large geographic area, but they also precipitate closures of popular recreation areas in the name of public safety. For example, in late September 2022, hundreds of kilometers of forest roads and nearly 150 trails

were closed due to the Cedar Creek Fire in the Willamette and Deschutes National Forests. The U.S. Forest Service also closed 86 recreation sites, including 28 campgrounds, and large sections of the Pacific Crest Trail across the two national forests. These closures came on the heels of the 2020 Labor Day fires (e.g., Beachie Creek, Lionshead), which led to closure of 19 popular trailheads, eight recreation sites, and numerous forest roads. Many of these closures may persist until summer 2023. The full economic impact of these and other recent fires, such as the Eagle Creek fire in the Columbia River Gorge, on Oregon's outdoor recreation economy has not yet been estimated. More assessment is also needed to understand the economic impact of a recreation experience that is affected by a prior wildfire (e.g., hiking through a burned area rather than an old-growth forest). Initial work suggests that the Eagle Creek fire may have reduced overall recreational visits to the area and induced a spatial redistribution of visits to specific sites (White et al. 2022).

Migration

Key factors in people's motivation to live in Oregon are the local environmental quality and the amenities associated with our climate. In other words, climate is a key factor in state residents' quality of life. A recent national analysis of predicted quality-of-life changes due to climate change suggests declines across much of the country (Albouy et al. 2016). Areas of Oregon west of the Cascades are an exception, and people in that region may benefit from climate change because of improvements to climate amenities in the future (Albouy et al. 2016). This result suggests people may want to move to Oregon due amenity shifts from climate change.

Climate migration is the temporary or permanent movement of a person or groups of persons, primarily in response to sudden or progressive changes in the environment due to climate change, within a country or across an international border. Although transboundary climate migration receives the most media attention, the majority of migration is within-country. Challenges result from the speed of climate change the number of people it affects. Temporary migration in response to climate stressors is already happening on a regular basis (e.g., evacuation associated with wildfires). The ability to migrate is a function of mobility and resources. Accordingly, the people most vulnerable to climate change are not necessarily those most likely to migrate.

In the United States, 162 million people—nearly half of the country's population—will most likely experience hotter temperatures and less rainfall. By 2070, if carbon emissions continue to rise, at least four million Americans may live in places outside the ideal range of conditions for human life (Xu et al. 2018). One in 12 residents of the southern United States may move toward California, the Mountain West, or the Pacific Northwest over the next 45 years because of climate influences alone (Fan et al. 2018). Such a shift in population is likely to increase poverty and widen the gulf between the rich and the poor. It will accelerate rapid urbanization of cities not prepared for the burden. People are likely to move to Oregon in response to climate change, and the population and economic production of the Pacific Northwest and Intermountain West may increase by 15 percent and 10 percent, respectively, by 2065 due to climate migration from other areas of the country (Fan et al. 2018). On paper, increased population and economic productivity may be viewed favorably, but such changes may create economic disruption, such as housing shortages and stressed infrastructure, if areas receiving migrants are unprepared for the magnitude of the change.

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Natural Systems

Natural systems, a term used in Oregon's 2021 Climate Change Adaptation Framework to encapsulate terrestrial, aquatic, coastal, and marine ecosystems, encompass the structure, composition, and function of life at all levels, from genes to biomes (Franklin 1981, Noss 1990). Structure often refers to the complexity of vegetation strata, such as grasses and herbaceous flowering plants, shrubs, and trees. Composition usually means the identities of species. Function generally includes ecological and evolutionary processes that sustain life. The fifth Oregon Climate Assessment explored the extent to which scientific evidence suggests that species in Oregon and the Northwest may be able to adapt to projected changes in climate, and examined the potential responses of several species of concern across the state to anticipated climate change.

In the first half of this section, Still and colleagues describe efforts to document foliage scorch, changes in tree growth, and tree mortality following extreme heat in the Pacific Northwest during June 2021. They also investigate how trees' use of water during that heat wave may have affected scorch and growth. Emerging research, including numerous studies in the northwestern United States, underscores that even when the current ecology of a species is well understood, it often is difficult to predict with confidence how the species will respond to climate extremes and trends. Challenges to such predictions in part reflect that climate change interacts with land-use change, other human-caused and natural environmental changes, and interactions among species (Biel and Hacker 2021, Carlson et al. 2021, Cinoglu et al. 2021, Reed et al. 2021). In both aquatic and terrestrial systems, the duration of a climate anomaly, such as a heat wave, also may affect stress, mortality, and population persistence (Bradford et al. 2022). Furthermore, responses can vary among events; for example, two apparently similar marine heat waves may not induce the same changes in distribution, abundance, or reproduction of a given species (Thompson et al. 2022).

In the second half of this section, Armstrong explains that although seasonally warm waters sometimes have been discounted in efforts to conserve Pacific salmon and other cold-water salmonids, those waters may in fact contribute to the fishes' potential for growth and survival during cooler periods of the year. Additionally, Armstrong and other researchers are discovering that some populations of salmonids may be more tolerant of high temperatures than previously understood. Research in the North Pacific Ocean indicated that pink salmon (*Oncorhynchus gorbuscha*) also may be fairly resilient to ocean acidification (Ohlberger et al. 2021).

When models of species' responses to climate change incorporate probabilities of adaptation, estimates of survival and area occupied usually are higher than if adaptive processes were not modeled (Garzón et al. 2011). In some cases, adaptations of species to environmental change may reflect temporary modifications of behavior, appearance, or physiology. In other cases, adaptive responses may result from adaptive evolution: heritable genetic changes that affect individuals' observable traits and increase probabilities of persistence of populations or species (Reed et al. 2011). Some evidence suggests that increases in temperature have little effect on rapid evolution of body size, developmental rate, or fertility among ectothermic animals (those that cannot regulate their body temperatures) (Grainger and Levine 2022). However, new research on birds and mammals in diverse ecosystems around the world implied that some animals' capacity for adaptive evolution may be as much as double that previously estimated (Bonnet et al. 2022). Similarly, some have suggested that at least until about the year 2100, certain groups of marine invertebrates that form shells may be able to adapt to ocean acidification (Leung et al. 2022). Natural systems are

variable and unpredictable. Some species and processes undoubtedly are being harmed by climate change, yet others may prove surprisingly durable.

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Impacts of the June 2021 Heat Dome on Pacific Northwest Forests

Chris Still, Linnia Hawkins, and Adam Sibley

Introduction

Following two years of drought, many areas of the Pacific Northwest and British Columbia experienced record-high air temperatures during an extreme heat wave ("heat dome") in late June 2021. The heat dome was among the most extreme heat waves ever recorded globally, and the most intense in the observational record for the Pacific Northwest (Thompson et al. 2022). The high air temperature during the heat dome coincided with the longest photoperiod and greatest solar insolation of the year, driving sunlit foliage temperatures 5–10°C (9–18°F) above the air temperature. At midday on the hottest day of the heat dome, the upper canopy air temperature at the H.J. Andrews Experimental Forest, a U.S. National Science Foundation Long Term Ecological Research site near Blue River, Oregon, was ~42–44°C (108–111°F), and sunlit foliage was close to 50°C (122°F) for several hours. This foliage temperature is a known threshold at or above which many plant tissues are damaged, and the combination of excess heat and high light intensity is especially damaging to leaves (Teskey et al. 2014).

Foliage Scorch Reports

Numerous reports of widespread foliage scorch and leaf drop in multiple tree species in forests on the west side of the Oregon Coast Range and Cascade Range followed the heat dome (Figure 1). Western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) seem to have been affected most strongly, but Douglas-fir (*Pseudotsuga menziesii*) and various alder (*Alnus*) and maple

Figure 1. Satellite imagery of an area near Garibaldi, Oregon, from before (10 June) and after (9 July) the 2021 heat dome. Yellow arrows indicate particularly clear foliage scorch. Imagery from Planet Labs, Inc.

(*Acer*) species also were affected. The worst foliage scorch seemed to be on trees and saplings with direct solar exposure and on south-facing slopes (Figure 2). Initial estimates from aerial surveys conducted by the U.S. Forest Service indicated that more than 230,000 ha (888 mi^2) of forest were

Figure 2. Foliage scorch from the 2021 heat dome at the leaf, whole-tree, and landscape levels. Photographs clockwise from top left: Ardeshir Tabrizian (*The Oregonian*), Adam Sibley, Dave Shaw.

affected in Oregon and Washington alone, with some of the most extensive damage in conifer forests dominated by Douglas-fir trees. These surveys also indicated that trees on south- and west-facing exposures were more severely scorched than those on other aspects, and that scorch was more prevalent in typically cooler, coastal mountains and the Cascade Range foothills than in hotter, lower elevation forests.

In response to the initial reports of foliar scorch, a team of scientists and forest managers at Oregon State University and the U.S. Forest Service asked people who observed scorch to report their observations at a website originally created by the Oregon Department of Forestry to survey effects of drought on forests (tinyurl.com/heat-wave-foliage-scorch). Because the website was developed by the Oregon Department of Forestry and the National Drought Mitigation Center to report drought

impacts on trees, we asked participants to note in the "Description and/or caption information" of the survey that they were reporting "impacts of the June 2021 heat wave" and to use the phrase "foliage scorch." These notes and terms allowed us to retrieve the observations and map and analyze this extreme event. Ninety-one reports (Figure 3) and 185 photographs were submitted.

Figure 3. Reports of scorch impacts submitted to the National Drought Mitigation Center and Oregon Department of Forestry website (left panel) and examples of photographs of scorch on a coniferous tree (center panel) and broadleaf tree (right panel).

Biological and Ecological Impacts of Heat Stress

There is increasing recognition that heat waves can lead to widespread reductions in tree growth and eventually mortality (Breshears et al. 2021). As the frequency of coincident heat waves and drought increases across the conterminous United States (Alizadeh et al. 2020), understanding the environmental drivers, biophysical and physiological mechanisms, and ecological consequences of damage to forests is of broad relevance. Despite within-tree and geographic patterns of scorch severity and mortality (Figure 2), the physiological and biophysical mechanisms that led to leaf death in some trees and not others are not known. Several factors could have made some trees relatively more susceptible to scorch, including slope and aspect, genetic differences, temperature acclimation at the time of the heat dome, hydration status of foliage, foliar phenology, and foliar microbes.

Heat Dome Impacts on Ecosystem-Scale Carbon and Water Cycling

The near-term and long-term physiological causes and consequences of foliage scorch and heat stress at leaf, tree, and ecosystem levels are unknown. The numerous effects could range from impaired metabolism of surviving leaves to smaller stem diameter to canopy die-back and eventual tree mortality (e.g., Filewod and Thomas 2014). Meristems—tree tissues that are essential to recovery and plant growth—also may have been damaged by the high temperatures. Prior research on Douglas-fir suggested that growth is likely to cease when heat waves occur during long photoperiods (Ford et al. 2017).

Several research stations throughout the U.S. Pacific Northwest and in British Columbia, Canada, monitor carbon and water exchanges between the atmosphere and forested ecosystems. These data can provide insight into the response of these forests to extreme heat, and how the heat dome affected forest physiology. Two of these stations monitor forests dominated by Douglas-fir

trees: one on Vancouver Island, Canada (CA-Ca3), and one just east of Vancouver, Washington, near the Columbia River (NEON-WREF). These two forest monitoring stations have measured weather, photosynthesis and respiration, and evapotranspiration since 2001. During the 2021 heat dome, temperatures at both sites were the highest recorded since their inception. The maximum air temperatures reached 36°C (97˚F) at CA-Ca3 and 40°C (104˚F) at NEON-WREF, both of which were more than three standard deviations above the mean for this time of year.

During the heat dome, both forests lost considerable water through evapotranspiration (Figure 4). At NEON-WREF, evapotranspiration was more than twice as high as the historical average rate and well outside the range of historic variability. At CA-Ca3, the rate of evapotranspiration was at the upper range of historical rates for June, but in the months following the heat dome the evapotranspiration rate decreased dramatically, falling below the historic range for the remainder

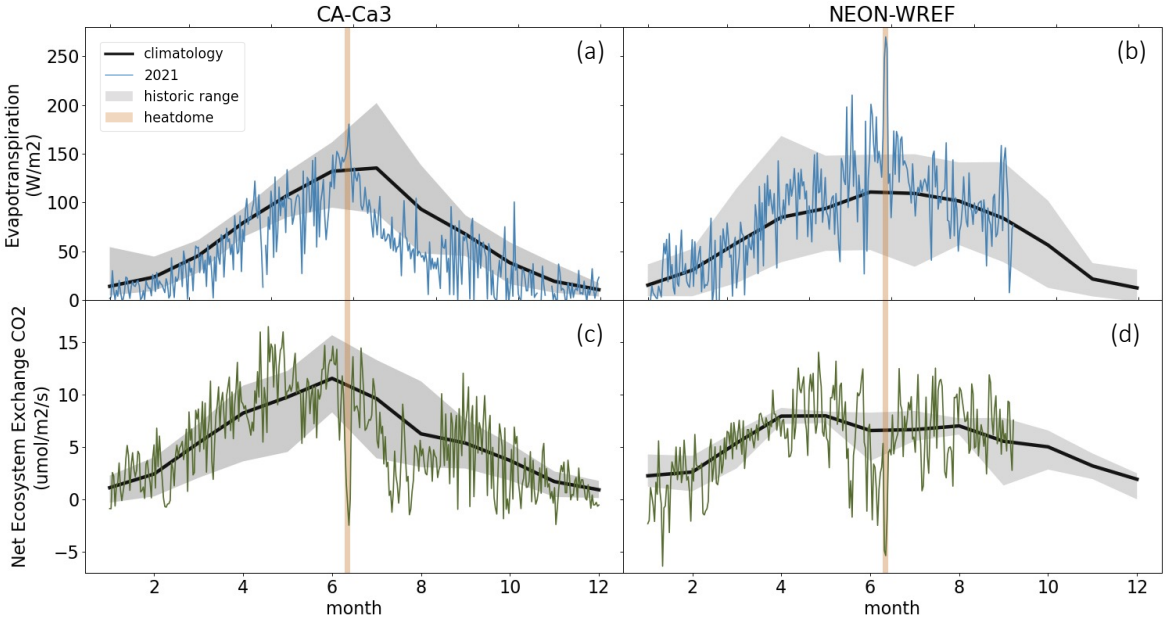

Figure 4. Evapotranspiration (top) and net ecosystem exchange of carbon dioxide (bottom) in two Douglas fir dominated forests in British Columbia, Canada (CA-Ca3, left panels) and the U.S. Pacific Northwest (NEON-WREF, right panels). Black lines represent the monthly mean, averaged across 2001-2021. Grey shading represents the range of historical monthly mean values (maximum and minimum). The time series of evapotranspiration (blue line) and net ecosystem exchange (green line) are daily mean rates during 2021, and the shaded orange band represents the heat dome in late June 2021.

of the growing season. Net ecosystem exchange (NEE) is the difference between photosynthesis and respiration. In an average year, NEE at both sites is positive throughout the growing season: both are removing carbon dioxide from the atmosphere. During the heat dome, NEE was negative, meaning that carbon dioxide was released to the atmosphere. The transpiration and NEE fluxes at these sites indicated that although the stress to trees during the heat dome was extreme at both sites, the trees at NEON-WREF were able to recover, whereas those at CA-Ca3 were stressed throughout the remainder of the growing season. More research is needed to identify the mechanisms and possible thermal thresholds beyond which photosynthesis and transpiration are hindered for prolonged periods, and to clarify the long-term consequences.

Looking to the Future

The June 2021 heat dome in the Pacific Northwest was an example of an extreme event exacerbated by human-caused climate change (Philip et al. in press), and it is highly likely that the duration, intensity, and frequency of heat waves will increase as the climate continues to warm (Perkins-Kirkpatrick and Gibson 2017, Vose et al. 2017). Ecosystems are likely experiencing novel conditions, and the effects are difficult to predict.

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The Contribution of Warm Water to Oregon's Cold-Water Fisheries

Jonny Armstrong

Salmonids, such as Pacific salmon, trout, and char, are among the most important fish taxa in Oregon because they play major ecological roles (Gende et al. 2002) while also provisioning recreational, commercial, and subsistence fisheries. As cold-water fishes, salmonids perform poorly at higher temperatures. In general, any water body that could provide a comfortable swimming hole for humans, with summer temperatures above 20˚C (68˚F), is suboptimal for salmonids. As climate change increases the spatial extent, duration, and severity of summer heat waves, a common conservation and management response is to identify and conserve the portions of basins that are not affected by such events (Isaak et al. 2015). These perennially cool areas almost exclusively are in high elevation tributaries fed by snowmelt. As conservation increasingly prioritizes such salmonid habitat as climate change refugia, the lower, warmer portions of basins are devalued and considered to be poor investments (Armstrong et al. 2021). However, seasonally warm waters may still contribute to fisheries and merit conservation action.

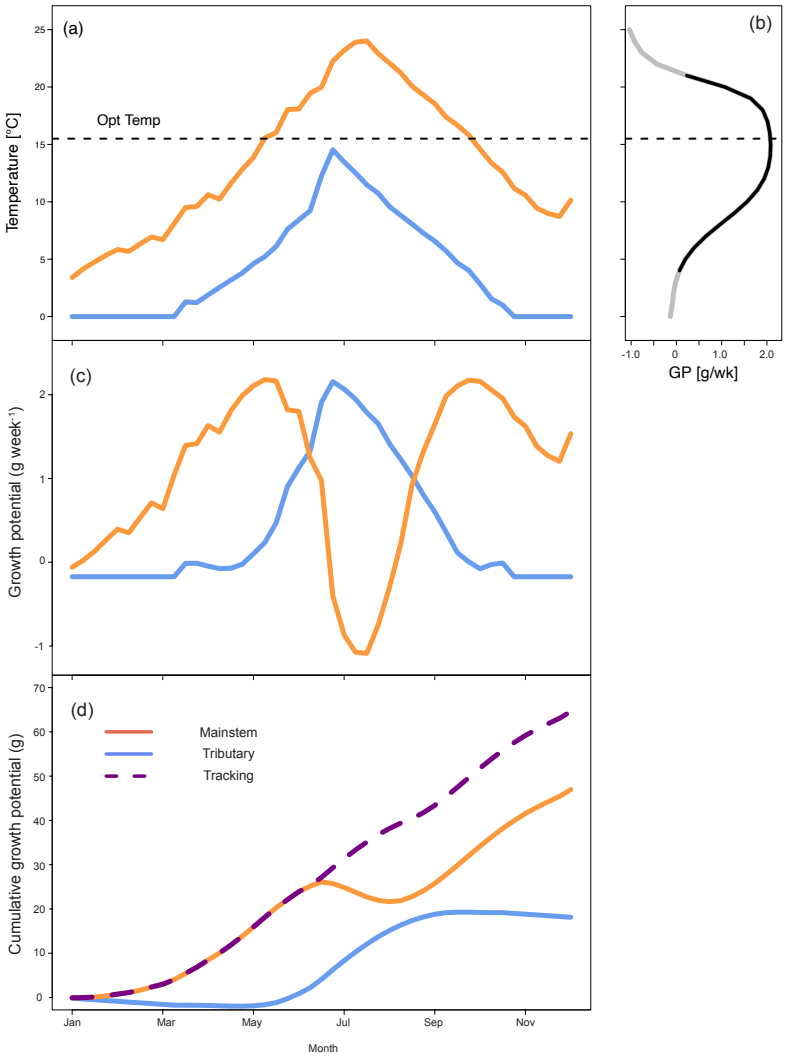

Figure 1. Variation in seasonal patterns of temperature and physiological performance across watersheds. (a) Contrasting mainstem and tributary water temperatures in the John Day River, Oregon. (b) A scope for growth curve for a cold-water fish (shaded black where growth is positive). (c) Incorporating the time series of temperature into the scope for growth model yields seasonal patterns of growth potential for headwater and mainstem habitat. (d) Cumulative growth potential for a sedentary fish in the mainstem or tributary habitat, or for a mobile fish that uses both habitat types to maximize growth potential. Figure adapted from Armstrong et al. 2021.

Water bodies that are too warm for salmonids during summer are thermally optimal at other times of year, when perennially cold habitat may be suboptimal (Figure 1). Temperatures below about 10˚C (50˚F) reduce physiological performance of most salmonids (Brett 1971). Although thermal optima differ among populations and species, peak performance usually occurs at temperatures of about 10–20˚C (50–68˚F) (Zillig et al. 2021). Streams that are thermally suitable in summer

tend to be suboptimally cold during the remainder of the year, whereas streams that are too warm during summer tend to be optimal in both autumn and spring (Figure 1, 2) (Armstrong et al. 2021, Hahlbeck et al. 2022). Indeed, areas with higher summer temperatures typically enable fish to grow more throughout the year than perennially cold areas (i.e., they offer more cumulative growth potential). Thus, cold and warm waters provide asynchronous, high-quality habitat for cold-water fishes (Kaylor et al. 2021), and either habitat type by itself tends to be thermally constraining for much of the year (Figure 1). Spring-fed rivers that have constant temperatures are an exception to this general pattern.

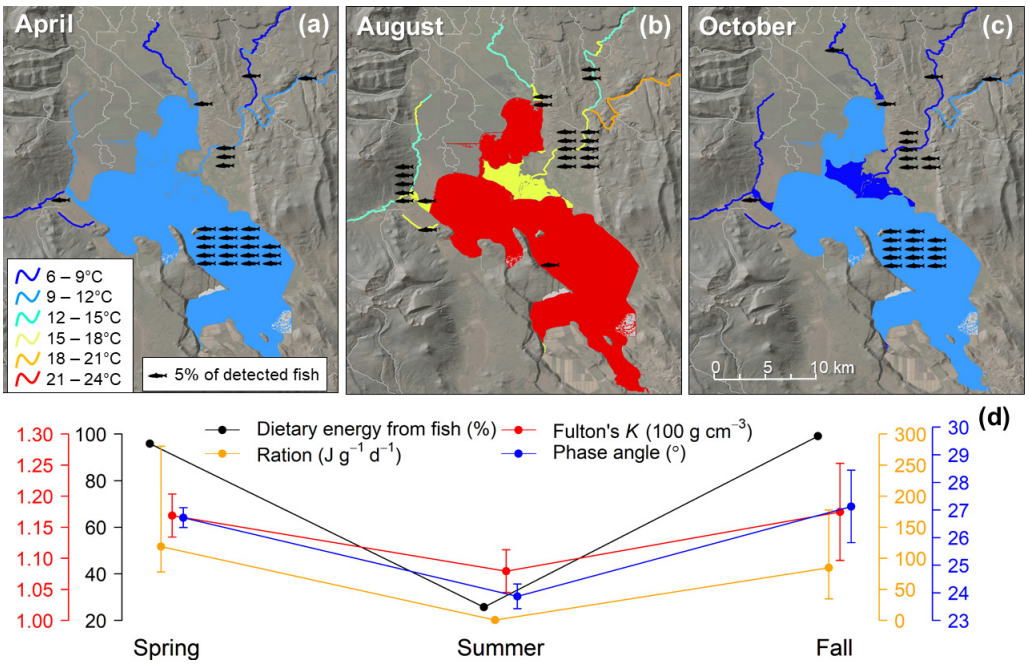

Figure 2. Example of cold-water fish exploiting seasonally warm habitat. Upper Klamath Basin with monthly mean water temperatures and redband trout habitat use during (a) April, (b) August, and (c) October, specified by the legend in (a). Use sums to >100% because some fish used multiple habitats in a month. (d) Foraging and energetic condition of redband trout in spring (in the lake), summer (in tributaries), and fall (in the lake). Each metric and its axis are coordinated by color as specified in the legend. Values of energetic condition metrics (K and phase angle) are expressed as mean (points) and normal 95% confidence intervals (bars). For right-skewed daily ration, a gamma distribution was used to estimate median and 95% confidence intervals. Dietary energy from fish represents the percentage of total dietary energy (summed across individuals) that is derived from forage fish. Figure from Hahlbeck et al. 2022, used with permission.

Although stressful summer conditions may preclude warm habitat from contributing to the growth of fishes that are sedentary, and therefore must tolerate the full range of conditions at a site, salmonids are highly mobile and are known to move among habitats that are complementary (Figure 1d) (Colyer et al. 2005, Petty et al. 2012, Bentley et al. 2015, Hahlbeck et al. 2022). The most striking example of such movement in the Pacific Northwest is the anadromous migrations of salmon and steelhead (*Oncorhynchus* spp.) between marine foraging habitat and freshwater juvenile rearing habitat. Salmonids also move over smaller distances at other times of the year to exploit ephemeral habitat.

Salmonids often exploit productive foraging habitats during autumn, winter, or spring, but leave these areas when they become stressful or lethal during summer. An extreme yet ubiquitous example is that of ephemeral streams that become dry in summer. Stream drying can occur across areas with

diverse climate and hydrology and is a conspicuous threat to juvenile salmon in rain-dominated tributaries in the Coast Range or the Cascade Range foothills. For example, many tributaries of the Rogue River become hot or dry during summer and early autumn (Everest 1973). However, these intermittent tributaries still support large runs of steelhead. Adult steelhead spawn in these tributaries during winter, rear during spring, and emigrate to the perennial mainstem of the Rogue River before summer drying. Similarly, ephemeral streams in the Smith River basin supported high rates of growth of juvenile coho salmon (*Oncorhynchus kisutch*) that moved to these habitats during winter (Ebersole et al. 2006). These ephemeral habitats are important for population productivity, yet are downgraded by climate-informed planning that is based on their poor summer conditions.

Seasonal movement can allow salmonids to exploit water bodies in which temperatures and other conditions during summer are lethal. For example, during summer, intense cyanobacteria blooms occur in Upper Klamath Lake (Platt Bradbury et al. 2004). The lake also has maximum summer temperatures above 25°C (77°F), pH levels approaching 10, and periods of severe hypoxia (low oxygen levels). These conditions generate mass mortality of fish taxa that are far more tolerant than salmon and trout (Martin and Saiki 1999, Perkins et al. 2000). Despite these summer hazards, the lake serves as high-quality foraging habitat during other seasons. Redband trout (*Oncorhynchus mykiss newberri*) move to the lake to gorge on forage fishes, and grow rapidly when temperatures are physiologically optimal in spring and autumn. Trout leave the lake during summer and move to spring-fed tributaries that remain cool year-round (Figure 2). However, although these summer refuges are spatially extensive and less impaired than the lake, redband trout do not grow in them (Figure 3). Accordingly, large-bodied trout require more than perennially cold water. Instead, they feed and grow in waters with seasonally extreme temperatures that would likely receive a low rank in climate-informed planning (Hahlbeck et al. 2022). A key uncertaintly is whether populations of small-bodied nonmigratory trout can persist in perenially cool tributaries without the contribution of large-bodied migratory fish, which produce more eggs and may reduce the risk of extirpation from wildfire or other disturbances.

Although redband trout in the Klamath River basin move long distances among adjacent water bodies, some populations survive in seasonally warm habitat by moving shorter distances within rivers or lakes. For example, some coastal cutthroat trout move to the floodplain of the mainstem Willamette River during summer, where upwelling springs provide thermal refuges that are up to ~7°C (12.6°F) colder than the adjacent mainstem (Barrett and Armstrong 2022). These fish appear to remain in the thermal refuges for weeks or months, but other salmonid populations may continue to exploit mainstem habitat through feeding forays or by feeding at thermoclines between habitat types (Brewitt et al. 2017). Fish may be able to feed for tens of minutes at a time in warm habitat before their body temperatures fully equilibrate (Pépino et al. 2015)

Cold-water fish use three general tactics, migration, movement, and tolerance, to persist in seasonally warm lakes and mainstem rivers (Barrett and Armstrong 2022). As described above, fish can migrate over long distances to cold tributaries, move over shorter distances to cold patches nested within warmer habitat, or tolerate warm conditions through physiological adaptations. There is renewed uncertainty about the temperatures that salmonids can tolerate before their physiological performance declines. For decades, salmonid physiology was assumed to be similar across populations or even species, and bioenergetics models for a given population often were parameterized on the basis of data from other populations or species. However, there is increasing recognition that thermal physiology, like many other traits in salmonids, may be locally adapted and therefore vary within species across space (Zillig et al. 2021). The parameters for bioenergetics

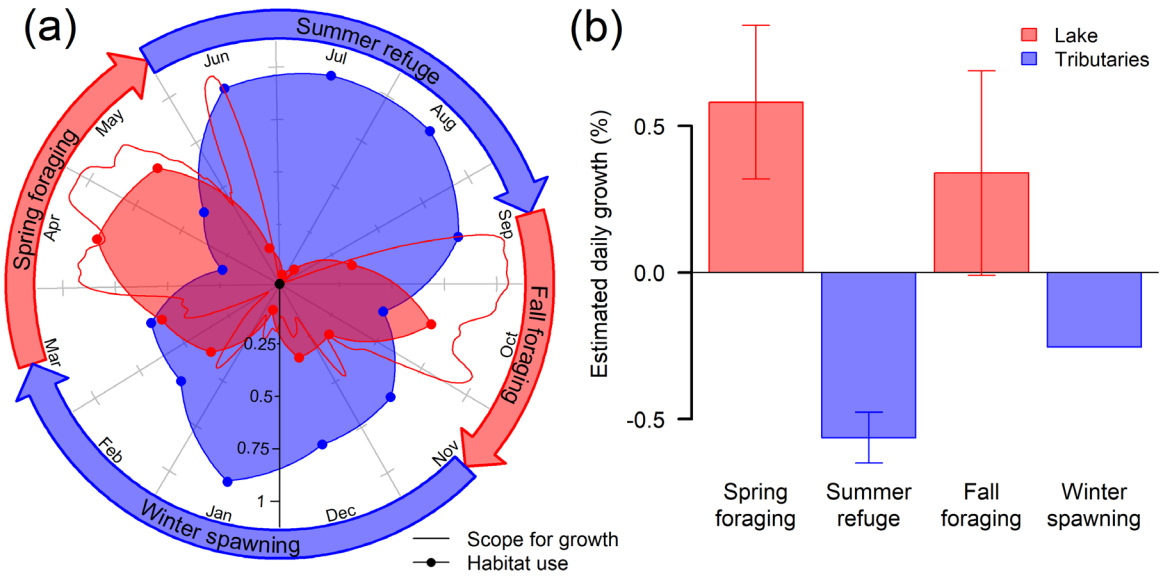

Figure 3. Complementary warm and cool habitat supports a migratory coldwater fish. (a) Biannual migrations between lake and tributary habitat by redband trout in the Upper Klamath Basin. Migration stages (arrows on outer ring) are based on congruence among telemetry, diet sampling, and spawning surveys. Lines bounding shaded areas within plot represent monthly habitat use, expressed as a proportion from 0-1 (shaded area). The red line indicates daily potential for growth in the lake given water temperature, expressed as percent body weight per day. Negative values in summer appear equivalent to zero. (b) Predicted daily growth during each migration stage (mean ± 95% CI), based on bioenergetics modeling and estimated cost of spawning in migratory redband trout. Seasonally warm lakes provide positive growth that appears to fuel the behaviors expressed in cool tributaries. Figure from Hahlbeck et al. 2022, used with permission.

models are now being updated for northern and southern populations. For example, maximum food consumption rates of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) now are known to occur at about 18–22˚C (64–72˚F) in southern populations, whereas the published parameter used for the prior ~20 years was 15˚C (59˚F) (Plumb and Moffitt 2015). Ongoing efforts to quantify thermal performance at the population level should help to refine understanding of variation in physiology among individual members of the same species.

In the wild, many ecological variables interact with a fish's physiology to mediate how well fish can adapt to warming temperatures. Laboratory studies can only go so far in predicting biological responses to climate change. However, to protect wild fishes, researchers are typically not permitted to sample when temperatures exceed 18˚C (64.4˚F). This temperature is about 10˚C (18˚F) below the lethal temperatures for most salmonids, so it cannot simply be assumed that waters too hot to sample are not being used by fish. In fact, recent bioenergetics research suggested that the 18°C threshold could be physiologically optimal for some populations (Plumb and Moffitt 2015). One way to resolve uncertainty about biological effects of water temperature is to implant fish with small transmitters that track their location and provide data on water temperature and the activity and survival of the fish throughout summer. This approach to studying fish distributions can yield novel insights not possible from sampling fish at fixed locations. For example, in the mainstem Willamette River, about 100 trout were tagged in spring and tracked weekly until autumn (Barrett and Armstrong 2022). About 10 percent of the population moved to floodplain thermal refuges or migrated to tributaries, whereas ~90 percent remained in the adjacent mainstem, where the temperatures sensors on their tags transmitted readings up to 22.5˚C (72.5˚F). This result surprised us because cutthroat trout are conspicuously abundant in thermal refuges during summer, but

difficult to observe in the mainstem due to sampling restrictions and low water clarity. Presence-absence data might lead one to assume that the mainstem was too warm for cutthroat trout during summer, yet the vast majority of tracked fish did not leave the mainstem even as it reached temperatures that likely were physiologically suboptimal (Anlauf-Dunn et al. 2022).

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Land-Use Law and Climate Change

Sarah J. Adams-Schoen and Michelle Smith

Introduction

Oregon's capacity to adapt to and mitigate climate change is determined in large part by the state's development patterns, including the placement and design of structures and infrastructure. Because state and local land-use laws control how and where development occurs, they play a key role in determining whether Oregon will reduce its emissions of greenhouse gases, preserve and increase the capacity of natural and working lands to sequester carbon, and increase the resilience of human communities to climate change and related risks (Salkin 2008, Stone 2009, Revi et al. 2014, Adams-Schoen 2018, Rogelj et al. 2018, OGWC 2021, Sullivan and Tarlock 2022). Here, working lands refers to forests harvested for timber, lands used for agriculture or livestock grazing, and parks and open spaces used for recreation.

Land-use laws significantly influence the geography of human development, including, for example, the size, shape, and growth rate of cities. Within human developments, land-use laws regulate the intensity and spatial distribution of land uses and strongly affect both the structural resilience of buildings and the resilience of communities to climate-related vulnerabilities such as extreme heat, flood, and wildfire (Rosenzweig 2011, Gencer et al. 2018, Sullivan and Tarlock 2022). For example, land-use laws can help communities avoid or mitigate risks related to development in flood- and wildfire-prone areas by mandating setbacks to maintain defensible space, requiring developments to conform with building criteria, and using regulatory mechanisms to shift development away from vulnerable areas (Adams-Schoen 2018). Land-use laws can also support both mitigation and adaptation strategies by, for example, encouraging or requiring protection and restoration of wetlands, dunes, and other natural systems that store carbon and buffer communities from the impacts of natural hazards such as floods (Telesetsky 2020). Additionally, planned high-density development can reduce carbon emissions from gasoline-powered vehicles and contribute to the maintenance of natural systems (Adams-Schoen 2018, Lwasa et al. 2022).

Oregon is a leader in harnessing land-use law to address several of the key drivers of climate change, such as urban sprawl and accompanying reductions in the area of natural and working lands. Recent reforms of Oregon's land-use and housing laws and related regulations support four climate goals: reduction of greenhouse gas emissions, carbon sequestration, increasing community resilience to climate-related risks, and more equitably distributing environmental benefits and burdens. However, we conclude that Oregon is not fully utilizing state and local land-use laws to support achievement of climate goals (Table 1).

In the following sections, we address six major points. First, the foundation of Oregon's land-use system consists of 19 statewide land-use planning goals and their implementing regulations, which prescribe the content of local land-use plans and laws and the implementation of those laws. The goals have largely shaped Oregon's land uses to address key concerns of the early 1970s, the period in which they were adopted. The goals do not expressly address climate change. Incorporation of climate considerations into the statewide planning goals and their implementing regulations provides a significant but unrealized opportunity to align Oregon land-use law and public and private land-use actions with the state's climate goals.

Second, by prioritizing the prevention of urban sprawl and the preservation of farms and forests for nearly 50 years, Oregon land-use law constrained a development pattern that increases emissions of

		Reduction of greenhouse gas emissions	Carbon sequestration	Reduction of community vulnerability	Equitable distribution of benefits and burdens
Integrated land-use and transportation scenario planning and Climate-Friendly and Equitable Communities regulations	Strengths	Requires and supports metropolitan planning organization scenario planning to reduce vehicle miles traveled; supports preservation of urban growth boundaries (UGBs) and production of energy efficient housing	Supports preservation of UGBs	Supports preservation of UGBs; may increase housing choice and affordability; may increase access to schools and services for historically marginalized populations; may improve public health outcomes for historically marginalized populations; partially implements Anti-Displacement Toolkit	
	Weaknesses	Implementation timeline unlikely to decrease emissions sufficient to support 2035 climate goal	Implementation timeline unlikely to decrease UGB expansions sufficient to support 2035 climate goal	Implementation may displace historically marginalized populations, may not address inequitable distribution of climate-related burdens to low amenity neighborhoods with larger populations of historically marginalized residents, and may increase housing density in areas vulnerable to natural hazards	
Housing-related amendments to state and local law	Strengths	Supports preservation of UGBs and production of energy-efficient housing	Supports preservation of UGBs	Supports preservation of UGBs; supports production of lower-cost housing and increased access to high amenity neighborhoods	
	Weaknesses	Failure to address pre-2021 private land-use restrictions may reduce climate benefits		Potentially increases density in vulnerable areas; does not address inequitable distribution of burdens to low amenity neighborhoods with larger populations of historically marginalized residents	

Table 1. Recent land-use and housing law reforms.

greenhouse gases and vulnerability to climate-related natural hazards while decreasing carbon sequestration. Recent changes in Oregon land-use and housing laws have the potential to further constrain this development pattern.

Third, the gap between emissions reduction targets and performance in the transportation and land-use sectors is wide, largely because state and local land-use and transportation laws have not been amended or adequately enforced to facilitate achievement of the targets. In 2019 and 2020, the governor directed the state's climate agencies, including the Department of Land Conservation and Development and Department of Transportation, to address significant implementation shortfalls that resulted in the discrepancy between targets and performance.

Fourth, the Land Conservation and Development Commission's new Climate-Friendly and Equitable Communities Rules (2022) will, assuming they survive a challenge pending in the Oregon Court of Appeals (City of Cornelius v. Oregon Department of Land Conservation and Development [2022]), contribute to reductions in emissions of greenhouse gases by strengthening climate-responsive transportation and land-use planning in the state's eight major urban areas: Portland Metro, Salem/Keizer, Corvallis, Albany, Eugene/Springfield, Middle Rogue/Grants Pass, Rogue Valley/Medford, and Bend. However, given the rules' implementation timelines, they likely will not contribute appreciably to Oregon meeting its goals for reduction of emissions by 2035.

Fifth, reform of Oregon's housing laws since 2017, and amendment of state and local land-use regulations pursuant to that reform, will contribute to Oregon remaining a national leader in reducing urban sprawl and associated increased emissions, natural hazard vulnerabilities, and

conversion of natural and working lands. However, these laws are unlikely to result in sufficient changes in development patterns within the timeframe needed to support achievement of Oregon's 2035 targets.

Sixth, Oregon's Statewide Land Use Planning Goal 7, *Areas Subject to Natural Hazards*, which directs local governments to address natural hazards in local comprehensive plans, has not been interpreted or enforced to require local governments to plan for and adapt to the current and foreseeable effects of climate change (Sullivan 2020b). The state's recent climate adaptation guidelines place more emphasis on the need to prepare communities for climate-related natural hazards and encourage local governments to adopt adaptation strategies that recognize the disparate burdens that historically marginalized communities bear with respect to climate-related vulnerabilities. However, state law does not require local governments to adopt or implement climate adaptation plans. Additionally, state and local law continues to approach climate adaptation by focusing primarily on the structural resilience of buildings while allowing and, in some cases, encouraging development in vulnerable areas.

Oregon's Land-Use System

Oregon's land-use system, which is built on a foundation of state-developed goals that constrain and guide locally developed and implemented plans, offers opportunities for the state to respond to climate change. Spurred by a desire to prevent uncontrolled development and sprawl, Oregon adopted its state-led model of land-use planning in 1973 (Sullivan 2012). This new system created the Land Conservation and Development Commission, consisting of seven governor-appointed commissioners, as the state policy body to implement state land-use laws. The legislature directed the commission to adopt statewide planning goals, which established the state's policies on land use and development. The commission ultimately adopted 19 Statewide Land Use Planning Goals that address uses of urban and rural lands, coastal resources, farm and forest lands, natural hazards, affordable housing, economic development, and urban growth (DLCD 2019a, Adams-Schoen and Sullivan 2022).

Oregon's land-use system delegates implementation of the statewide goals to local governments, which are required to adopt comprehensive local land-use plans that are consistent with the statewide goals. Following acknowledgment by the Land Conservation and Development Commission that a plan conforms to the statewide goals, the plan becomes the basis for all local land-use laws and public and private land-use actions (Sullivan 2012).

The Land Conservation and Development Commission also adopts administrative rules that implement state land-use policies and oversees the Department of Land Conservation and Development, the state's land-use planning agency, which implements the Land Conservation and Development Commission's policies and supports implementation of these policies by local governments. A separate state agency, the Land Use Board of Appeals, replaces a generalist trial court in adjudicating most land-use disputes (Adams-Schoen and Sullivan 2022).

Role of Land-Use Law in Adaptation to and Mitigation of Climate Change

Oregon's land-use framework provides a significant opportunity to support the state's climate adaptation, mitigation, and sequestration goals. In many cases, changes in land-use laws support multiple climate goals. Adaptation refers to actions that help society adjust to the effects of climate change. Land-use laws are often characterized as facilitating climate adaptation through protection,

accommodation, and retreat (Grannis 2011, Grannis et al. 2012, Nolon 2013, Siders 2013, Adams-Schoen 2018). Protection refers to laws that attempt to maintain existing developments and defend them from climate threats; regulations that permit shoreline armoring are an example. Accommodation-based laws seek to permit continued development in vulnerable locations by aligning structural design with climate risks by, for example, requiring homes built in wildfire-prone areas to have vegetation setbacks or use nonflammable building materials. Retreat-based laws restrict or prevent new development in vulnerable areas and shift existing development to safer locations. Examples include laws that require, enable, or incentivize relocation of uses and structures and laws that prohibit or restrict some or all forms of development in vulnerable areas. The range of retreat regulatory strategies is large and diverse, ranging from buyouts and floodplain and wildfire-risk area regulations to transfers of development rights and urban growth boundary reconfigurations.

Land-use law is also integral to the attainment of mitigation and carbon sequestration goals (Shukla et al. 2019). Mitigation refers to reducing emissions of greenhouse gases. Land-use laws can support mitigation by, for example, prescribing compact development to reduce the distance that people travel from home to daily activities and encouraging low-carbon transportation options (NRC 2009). Other examples include laws that encourage or mandate energy-efficient building design and materials, reduce regulatory barriers to the development of renewable and low-carbon energy, and limit high-emission-generating uses, such as confined animal feeding operations.

Carbon sequestration refers to the capture and storage of atmospheric carbon dioxide. Land-use laws that restrict development of natural and working lands can support sequestration by maintaining carbon sinks, such as old-growth forests, wetlands, and coastal dunes (Sleeter et al. 2018). These regulations prevent the release of stored carbon from the conversion of natural lands and help to maintain existing carbon stores (Graves et al. 2020). Land-use laws that protect natural areas (e.g., by preventing or reducing development-related pollution) can also preserve and enhance the capacity of natural areas to sequester carbon (Graves et al. 2020). Additionally, land-use laws can, if properly tailored, increase the capacity of working lands such as farms and pastures to sequester carbon (Fargione et al. 2018).

Land-use laws that limit urban sprawl can promote the attainment of adaptation goals, targets for reduction of greenhouse gas emissions, and carbon sequestration. Urban sprawl increases the distance that residents typically travel by personal vehicle for work, school, and other activities; contributes to the loss of forests, grasslands, and other ecosystems that, when largely undisturbed, sequester carbon; and can increase the vulnerability of human populations to natural- and climate-related threats, such as by bringing human settlements closer to wildfire-prone vegetation (Stone et al. 2010, Jones and Kammen 2014, Radeloff et al. 2018). A key step in reducing sprawl is a thorough assessment of existing land-use laws and related regulations to identify those that contribute to sprawl. Examples include regulations that prohibit dense housing structures, such as apartment buildings and single-room occupancies; require the construction and dedication of land for off-street parking spaces as a condition of residential development (Figure 1); restrict the number of people who can live in a residential unit or geographic area; limit the percentage of a buildable lot that can be covered by one or more residential units; or limit the geographic expansion of cities. Careful tailoring is required to assure that urban growth boundaries and density increases do not generate offsetting inter-urban commutes and do not entrench existing disparities in access to affordable housing and areas of economic, social, and educational opportunity, which exacerbate climate vulnerabilities.

Figure 1. Off-street parking in downtown Corvallis. Source: Oregon Department of Land Conservation and Development, July 2022.

Although land-use laws have the potential to reduce the adverse effects of climate change, most were developed without consideration of climate science and have not been revised to reflect climate science. Many of these laws increase climate-related risks or create barriers to achieving climate-related goals (Grannis 2012, Siders 2013, Adams-Schoen 2018). For example, land-use laws may continue to permit or even create incentives for development in areas vulnerable to natural hazards or in areas that have mitigation potential. Examples include laws that allow development in flood- or wildfire-hazard areas or in wetlands or other natural areas, or that prohibit or prolong the time necessary to develop renewable energy infrastructure.

To date, many U.S. communities engaged in planning for climate change have focused solely on adaptation strategies (Adams-Schoen 2018, Schipper 2020). These strategies tend to focus on increasing the resilience of buildings by adopting requirements that protect individual structures from climate risks—for example, requirements that structures in flood-hazard areas be elevated at or above the base-flood elevation. However, even when new development can be designed for structural resilience, community resilience requires accounting for the economic and social costs of exposing residents and first responders to climate-related hazards, cost of infrastructure maintenance in vulnerable areas, impact of new development on adjacent areas, and loss of species and ecosystem function (Adams-Schoen 2018). Focusing on buildings while allowing development in vulnerable areas can also perpetuate community misperceptions about the risks presented by development (Schipper 2020).

Additionally, focus on buildings can divert attention from community-level resilience. Community-level resilience strategies require or create incentives to reduce the intensity of land uses in vulnerable areas and areas that can sequester appreciable amounts of carbon (Siders 2013, Adams-Schoen 2018). Examples include land-use regulations that permit only open space or recreational uses in vulnerable areas; designate existing higher-intensity land uses as non-conforming, which, under typical land-use laws, means that the existing use cannot be enlarged, expanded, or rebuilt if destroyed; or provide transferrable development credits that allow owners of property in vulnerable areas to transfer their development rights to parcels in less vulnerable areas, thereby recouping some of the economic value of their initial investment.

Assessment

Since 2004, Oregon policy has called for consideration of the effects of land uses on climate (Governor's Advisory Group on Global Warming 2004). In 2007, Oregon House Bill 3543 created the Oregon Global Warming Commission and adopted greenhouse gas emissions reduction targets of 10 percent below 1990 levels by 2020 and 75 percent below 1990 levels by 2050 (ORS 468A.205). In 2020, Governor Brown updated Oregon's emission reduction targets to 45 percent below 1990 levels by 2035 and 80 percent below 1990 levels by 2050 (Oregon Executive Order 20-04).

Since 2010, the state has recognized that consideration of climate in state and local land-use planning and actions is essential to meeting Oregon's legislatively adopted targets (OGWC 2010).

In 2011, the Oregon Global Warming Commission recommended that land-use planning processes include consideration of carbon emissions and storage. The commission also recommended that urban, forest, and agricultural land-use decision-making align with the state's climate goals (OGWC 2011). To this end, the commission recommended that cities accommodate residential and employment growth within existing urban growth boundaries; make public transit more convenient, frequent, accessible, and affordable; and redesign neighborhoods so schools, services, and shopping are easily accessible by walking, biking, or public transit (OGWC 2011). Furthermore, the commission recommended that transportation plans facilitate more transport by rail and less transport by trucks.

In 2020, the Oregon Global Warming Commission projected that, if current trends continued, the state would exceed its initial 2035 and 2050 targets by 23 and 54 million metric tons (MMT) of carbon dioxide, respectively (OGWC 2020). The Department of Land Conservation and Development subsequently reported that, if current trends continued, emissions from Oregon's transportation sector would exceed the state target by 400 percent by 2050 (DLCD 2022b).

However, in July 2022, the Oregon Global Warming Commission reported that modeling that incorporates 14 adopted and in-development state programs suggests that Oregon can meet the goal of reducing emissions to at least 45 percent below 1990 levels by 2035, assuming timely and complete implementation of the programs (OGWC 2022). The 14 programs do not include regional scenario planning pursuant to the new Climate-Friendly and Equitable Communities rules or urban densification pursuant to the 2017 to 2022 reforms of Oregon's housing and land-use laws.

Oregon's Statewide Land Use Planning Goals

The statewide goals have largely shaped Oregon's land uses to address key concerns of the early 1970s, including limiting urban sprawl and preserving forests, agricultural lands, and coastal dunes and estuaries. Because the goals and their implementing regulations prescribe the content of local land-use plans and laws and the implementation of those laws through, for example, development-permitting decisions, consideration of climate in the statewide goals provides a major opportunity to align Oregon land-use law and public and private land-use actions with the state's climate goals.

However, climate change is not expressly reflected in the goals, the implementing agency and courts have not interpreted the goals to require climate considerations, and Oregon has not reviewed or assessed the capacity of the planning goals and associated regulations to effectively address climate change. Furthermore, in 2021, the legislature did not act on a bill that would have amended Oregon's land-use system to add a twentieth statewide goal, which would have required local governments to integrate climate justice considerations into their comprehensive plans and land-use regulations.

In 2021, the Oregon Global Warming Commission recommended that the Department of Land Conservation and Development, with funding and direction from the legislature, analyze how the statewide planning goals and their implementing regulations could be amended to better protect and restore natural and working lands and increase sequestration (OGWC 2021). As part of the statewide goal analysis, the commission advised the Department of Land Conservation and Development to analyze actions it should take to direct and support local jurisdictions in addressing climate mitigation in their comprehensive plans and land-use regulations. With respect to sequestration, the commission emphasized Statewide Planning Goals 3 (Agricultural Lands), 4 (Forest Lands), 5 (Natural Resources, Scenic and Historic Areas, and Open Spaces), 16 (Estuarine Resources), and 17 (Coastal Shorelands).

Without legislatively enacted statewide planning goals that require climate considerations, local governments have no express mandate to consider climate in their comprehensive plans and land-use actions. Local governments are obligated to consider climate, however, when climate considerations are incident to other factors they are legislatively mandated to consider. For example, local governments must consider "social, economic, energy and environmental consequences" when expanding their urban growth boundaries under Goal 14 (Urbanization), establishing programs to protect open space and natural resource areas under Goal 5 (Natural Resources, Scenic and Historic Areas, and Open Space), adopting exceptions to statewide goals under Goal 2 (Land Use Planning), and identifying lands "suitable" for residential use under Goal 10 (Housing) (DLCD 2019a). Additionally, Goal 7 (Areas Subject to Natural Hazards) mandates that "Developments subject to damage or that could result in loss of life shall not be planned or located in known areas of natural hazards without appropriate safeguards" (DLCD 2019a).

Moreover, the state has no basis for reviewing plans with respect to climate responsiveness or requiring modifications of local comprehensive plans that do not address climate mitigation, and the state has not interpreted the Natural Hazards Goal to require plans to address climate adaptation. As a result, many current, approved comprehensive plans do not substantively consider climate adaptation or mitigation, and local land-use laws and decisions do not reflect state climate change goals and climate vulnerabilities.

Although the absence of explicit climate considerations in the statewide goals does not prevent local governments from adopting land-use laws that integrate climate science and state climate goals, most have not done so. Key barriers to local action include a lack of technical capacity, insufficient funding, and political constraints. Furthermore, land-use planning is often contentious because it affects private land uses, and local elected public officials are unlikely to act in the face of strong public opposition.

Decreasing Emissions of Greenhouse Gases

Transportation and Land-Use Sector Emissions Reduction Targets and Performance

The transportation sector accounts for nearly 40 percent of Oregon's greenhouse gas emissions (OGWC 2020). The majority of these emissions are from cars and light trucks in the state's eight major urban areas: the Portland metropolitan area (Metro), Salem and Keizer, Corvallis, Albany, Eugene and Springfield (Central Lane), Middle Rogue and Grants Pass, Rogue Valley and Medford, and Bend (OGWC 2018). As required by federal transportation law, the state has designated metropolitan planning organizations (MPOs) to coordinate transportation planning in each of these urban centers (49 U.S.C. § 5303, 1000 Friends of Oregon 2022).

The state passed laws in 2009 and 2010 that required the eight MPOs to consider how regional transportation plans could be revised to reduce emissions (HB 2001 [2009], sections 37–39; HB 2186 [2009], section 10; SB 1059 [Chapter 85, Oregon Laws 2010, Special Session], codified at ORS 468A.205). The 2009 and 2010 laws also required the Portland Metro MPO to develop and implement an integrated land-use and transportation scenario plan to reduce emissions from cars and light trucks. The laws directed the Land Conservation and Development Commission to adopt emissions reduction targets for each MPO; the Oregon Department of Transportation (ODOT) to adopt a state transportation strategy to reduce greenhouse gas emissions; and the Land Conservation and Development Commission and Oregon Transportation Commission to provide MPOs with policy leadership and decision-support tools, such as planning guidelines and computer modeling, to

forecast the emissions consequences of land-use and transportation actions. The Jobs and Transportation Act of 2009 directed the Land Conservation and Development Commission and ODOT to provide technical and financial support to the Portland Metro and Central Lane MPOs for scenario planning. Portland Metro completed its scenario plan in 2014 and subsequently amended its land-use laws pursuant to the plan (ODOT 2018). Central Lane completed a draft of its plan in 2015 but has not adopted the plan.

Figure 2. Cycling over Tilikum Crossing Bridge, Portland, Oregon. Photograph by Cole Keister.

The Statewide Transportation Strategy identified efficient land use as one of six general categories of strategies necessary for the transportation sector to contribute to achieving Oregon's emissions reduction goals (ODOT 2013). Efficient land-use strategies are those that promote efficient transportation via compact growth and development, reducing travel distances and enabling use of lower energy and zero energy transportation (Figure 2) (ODOT 2013). Examples of laws consistent with these strategies include those that support mixed-use development, limit expansion of urban growth boundaries, and promote consolidation of urban centers for freight shipping and operations (ODOT 2018). Although ODOT reported in 2018 that compact urban development is reliant on housing costs, generational preferences, and job locations (ODOT 2018), economics, urban studies, and land-use law research suggests that land-use regulations affect variation in the price of urban housing and play a larger role in shaping urban development than factors such as generational preferences and job location (Been et al. 2018).

In its most recent Statewide Transportation Strategy monitoring report, ODOT estimated that current and planned implementation of statewide transportation strategies would reduce emissions to 15–20 percent below 1990 levels by 2050, far short of the goal of reducing carbon emissions from the transportation sector to 75 percent below 1990 levels by 2050 (ODOT 2018). As of 2022, only the Portland Metro and Central Lane MPOs have undertaken scenario planning, and only Portland Metro has adopted and begun implementing a scenario plan. The Corvallis Area and Rogue Valley MPOs voluntarily completed strategic assessments of their existing plans and policies, identified potential approaches for reducing transportation-related emissions, and revised their regional transportation plans. Four of Oregon's eight MPOs have not conducted scenario planning or strategic assessments.

Although ODOT's 2018 monitoring report stated that the rates of limitation of urban growth boundary expansions and creation of dense mixed-use areas were consistent with goals in the

Statewide Transportation Strategy (ODOT 2018), data in the report indicated otherwise, and Appendix A of the report included the Department of Land Conservation and Development's finding that the state was not meeting the goal of limiting expansions of urban growth boundaries. Additionally, the goal of 20 percent of households living in mixed-use areas by 2020 was already met when the Statewide Transportation Strategy was published in 2012, and the data in the 2018 monitoring report suggested that Oregon is unlikely to meet the goal of 30 percent by 2035. The Department of Land Conservation and Development reported that most progress toward the goal was in the Portland metropolitan area, and other metropolitan areas have not progressed above the baseline (ODOT 2018).

Effects of Climate-Friendly and Equitable Communities Rules

In 2019, responding to slow progress toward meeting Oregon's emission reduction targets, Governor Brown sent a letter to the state's climate agencies—the Departments of Land Conservation and Development, Transportation, Environmental Quality, and Energy. The letter directed the Departments of Land Conservation and Development and Transportation to prioritize implementation of the Statewide Transportation Strategy. On 19 March, 2020, Governor Brown issued Executive Order 20-04, which included four directives to the Land Conservation and Development Commission and Oregon Transportation Commission: prioritize implementation of the Statewide Transportation Strategy, establish emission reduction-performance metrics, expedite amendment of transportation planning rules to ensure that the state's MPOs meet their regional emissions reduction goals, and comply with the legislative mandate to provide local governments with the funding and technical assistance needed to revise and implement their plans for reducing vehicle emissions. Executive Order 20-40 reiterated the need to amend state and local land-use and transportation regulations to implement state law.

Recognizing that the state is not meeting its emissions reduction targets for the transportation sector, the Land Conservation and Development Commission initiated a rulemaking proceeding in September 2020 to respond to Executive Order 20-04. The commission directed the rulemaking advisory committee to prioritize social equity in recognition of Oregon's record of inequity and bias in land-use planning, zoning law, and transportation investment (DLCD 2022a). After two years of community engagement, the Land Conservation and Development Commission adopted Climate-Friendly and Equitable Communities administrative rules on 21 July, 2022. The rules are intended to increase housing options and affordability in mixed-use neighborhoods designated by the MPOs as Climate-Friendly Areas (CFAs); improve walkability and alternative transit options in CFAs so residents can access jobs, schools, services, and other essentials without a car (Figure 3); improve, expand, and connect networks of sidewalks, bike lanes, and other transit infrastructure to decrease car dependence; reduce the amount of parking required as a condition of residential development; and focus local and regional transportation planning on decreasing vehicle miles traveled in cars and trucks (1000 Friends of Oregon 2022, DLCD 2022a).

The Climate-Friendly and Equitable Communities rules require cities and some other urban areas within the seven MPOs that have not developed an integrated land-use and transportation scenario plan to reduce emissions from cars and light trucks, designate CFAs, and amend their local laws to remove existing regulatory barriers to denser, more walkable development in the CFAs. The rules define CFAs as urban areas that contain, or are planned to contain, a mix and supply of housing, jobs, businesses, and services. CFAs must be served, or plan to be served, by high-quality pedestrian, bicycle, and transit infrastructure. For example, the CFA rules require MPOs to allow taller

residential buildings and adopt minimum density standards to help ensure that public transit can serve the CFA. The rules support the ongoing implementation of the Portland metropolitan area's existing regional scenario plan, the 2040 Growth Concept.

The Climate-Friendly and Equitable Communities rules' implementation timelines do not align with the state's emissions reductions targets. The rules require the seven MPOs that have not yet developed scenario plans to do so by 31 December, 2027 (Eugene-Springfield and Salem-Keizer) or 31 December, 2029 (the remaining MPOs); these are the existing deadlines for the MPOs' major updates to their transportation system plans. The rules allow the MPOs to extend these deadlines by applying to the Department of Land Conservation and Development. MPOs may also apply to the Department of Land Conservation and Development for alternative deadlines to amend their commercial, land-use, and bicycle regulations and to implement their updated transportation system plans (Oregon Administrative Rules 660-012-0012). Because developed plans take years to implement, the new rules likely will not lead to stabilization or reduction of vehicle emissions from any of the state's MPOs (except Portland Metro, which is already implementing its scenario plan) until 2030 at the earliest, and probably not until years later.

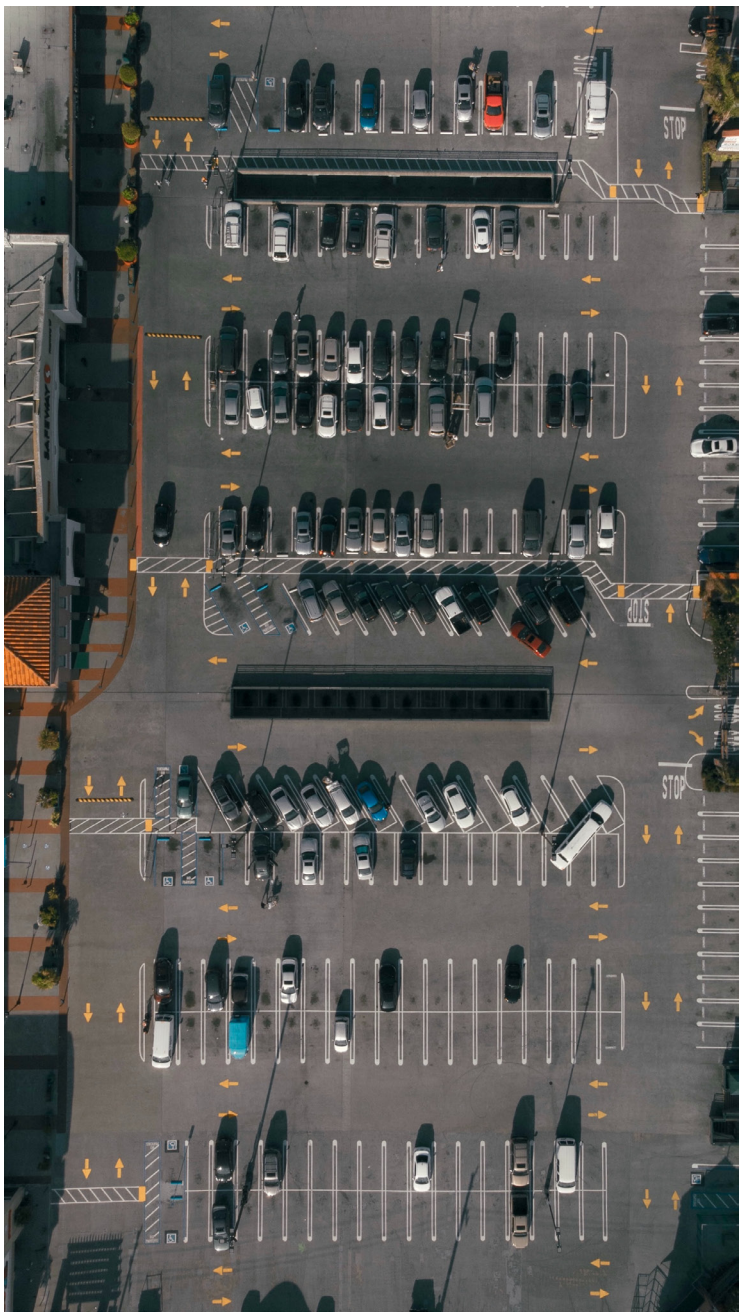

Figure 3. Climate-Friendly and Equitable Communities rules may help reduce Oregonians' reliance on vehicles to access jobs and services. Photograph by Hamza Erbay.

Therefore, although the new rules substantially improve the likelihood that local and regional integrated land-use and transportation regulations will help the state reduce emissions from the transportation sector (Boarnet and Handy 2014, American Association of State Highway and Transportation Officials 2021), the new rules will probably not support reduction of emissions to 45 percent below 1990 levels by 2035, a target that Executive Order 20-40 identified as necessary to meet the state's 2050 goal. Nor do the rules require local

or regional governments to specify how their planned transportation projects will allow the MPO to meet its share of the state's targets for emissions reductions by the transportation sector.

The land-use components of the Climate-Friendly and Equitable Communities rules are also unlikely to lead to significant reductions in emissions by 2035. The rules require local governments to study potential CFAs by the end of 2023 and designate CFAs by the end of 2024. The rules allow local governments to apply for extensions of the deadlines to designate and make comprehensive plan, zoning map, and code changes to implement the CFA rules. The latter actions necessarily precede changes in development patterns and practices. Local governments were required to begin applying the rules' reduced parking mandates to new development near frequent transit stops and certain other developments by 31 December, 2022. Local governments have until 30 June, 2023 to implement the other required parking reforms but may apply for an extension. All of the land-use components of the Climate-Friendly and Equitable Communities rules can be characterized as market-based strategies. Therefore, changes in land uses will only occur after local laws are amended, developers apply to build on land that the amended local laws regulate, and the new development is completed. Because the local law-amendment timelines allow for extensions and the emissions reductions will not occur until new development is completed, the land-use components of the Climate-Friendly and Equitable Communities rules are unlikely to result in reductions in emissions commensurate with the targets of 45 percent below 1990 levels by 2035.

Effects of Housing and Zoning Law Reforms

Prior to 2019, Oregon's land-use system did not constrain the use of single-unit residential zoning, a ubiquitous feature of zoning ordinances in U.S. cities, which is a major driver of urban sprawl (EPA 2018, Pendall 2021, Adams-Schoen and Sullivan 2022) (Figure 4). Typically, the single-unit residential zone limits residential development on each buildable lot within its boundary to a single dwelling structure that may be occupied by only one regulatorily defined family or household unit and that is surrounded by a yard with one or more paved parking spaces. Other residential structures, from duplexes to apartment buildings, are prohibited within the zone. As is the case in cities throughout the United States, cities in Oregon limited the vast majority of their residentially zoned land to detached single-unit homes. Because Oregon's land-use system authorizes cities to expand their urban growth boundaries when more land is needed to house growing populations, the local regulatory requirement that most residential land be dedicated to single-unit housing contributed to the expansion of urban areas and associated increases in emissions.

Oregon made history in 2019 when it passed House Bill 2001, which amended state law to require cities with populations of 10,000 or more to allow duplexes, and in the case of cities with populations of 25,000 or more, duplexes, triplexes, quadplexes, townhouses and cottage clusters, in areas that previously only allowed detached single unit homes (Adams-Schoen and Sullivan 2022). Oregon's statewide residential zoning reform, the first such statewide reform in the United States, was part of a series of amendments to the state's housing and land-use laws that included enactments in the 2017, 2019, and 2021 legislative sessions and the 2022 short session. Collectively, these laws require cities to utilize urban land more fully for needed housing (Sullivan 2020a).

In 2020, the Land Conservation and Development Commission adopted rules that filled in the details of House Bill 2001 and included model local codes to support cities in their implementation of the zoning reforms. The new rules include many standards intended to require cities to remove regulatory requirements that, individually or cumulatively, add "unreasonable cost or delay" to the

development of smaller, denser forms of housing in areas where only larger, detached single units had previously been allowed. For example, the rules limit the application of maximum density and lot coverage standards and minimum building and lot size standards. The rules also require cities to allow existing housing to be converted to multi-unit housing and place a cap on the amount of off-street parking that local zoning regulations can mandate for duplex, triplex, quadplex, townhouse, and cottage cluster developments. Maximum density and lot coverage standards, minimum building and lot size standards, and off-street parking mandates increase the amount of land used for housing and contribute to urban sprawl (LeDuc et al. 2000, Manville and Pinski 2020, Adams-Schoen and Sullivan 2022). Regulatory off-street parking mandates increase personal vehicle use and decrease use of mass transit and other lower-emissions forms of transportation (USDOT 2011, EPA 2018, DLCD 2020, LeDuc et al. 2000, Millard-Ball et al. 2022).

Figure 4. Single-use residential zoning is a major contributor to urban sprawl. Photograph by Porter Raab.

House Bill 2001 mandated prompt implementation by requiring cities to amend their comprehensive plans and land-use regulations to comply with the new law by 30 June, 2021, or 30 June, 2022, depending on the size of the city, and strictly limiting the bases for and scope of any extensions of the deadlines (Adams-Schoen and Sullivan 2022). Accordingly, in 2021 and 2022, cities throughout Oregon amended their local plans and regulations to conform to the new law. Ashland, Bend, Coos Bay, Eugene, Portland, Roseburg, St. Helens, and other cities exceeded one or more of the minimum requirements of the state regulations (Adams-Schoen and Sullivan 2022).

By requiring cities to utilize urban land more fully for needed housing and thereby decelerate the pace of urban growth boundary expansions, Oregon's housing and zoning law reforms will decrease the pace of urban sprawl and associated increased emissions and increase the energy efficiency of new housing units (LeDuc et al. 2020, Manville and Pinski 2020, Sullivan 2020a). Moreover, because the reforms included strict, legislatively mandated deadlines, local land-use decisions have been subject to the new laws since at least mid-2022. However, as is the case with other market-based strategies such as the land-use components of the Climate-Friendly and Equitable Communities Rules, changes in land uses and resulting emissions reductions will only occur after

developers apply to build on land that the amended local laws regulate, and the new development is completed. Accordingly, the housing and zoning law reforms may not result in sufficient changes in development patterns within the timeframe needed to support achievement of Oregon's 2035 targets. Additionally, the zoning law reforms did not invalidate pre-2021 private land-use restrictions that limit many lots to single-unit residential use. Both the validity and enforceability of these private restrictions under Oregon law and the extent to which they will impede residential densification and associated climate benefits remain unclear.

Carbon Sequestration

Compared to states without urban growth management laws, Oregon's land-use system has largely achieved its original purposes of preventing the conversion of farms and forests and limiting urban sprawl. Since the 1970s, western Oregon retained 89 percent of these lands and eastern Oregon retained 97 percent (Oregon Task Force on Land Use Planning 2009). The avoided conversion of natural lands attributable to implementation of the state's land-use planning system retained carbon storage in western Oregon equivalent to a reduction of 1.7 MMT of carbon dioxide per year (Cathcart et al. 2007).

However, research also suggested that Oregon could increase net sequestration in natural and working lands and waters by up to 9.8 ± 1.7 MMT of carbon dioxide emissions per year by 2050 (Graves et al. 2020). In response, the Oregon Global Warming Commission announced the goals of sequestering an additional 5 MMT per year in Oregon's natural and working lands and waters by 2030 and at least 9.5 MMT per year by 2050, relative to estimated net sequestration from 2010 through 2019 (OGWC 2021). These sequestration goals are in addition to Oregon's sector-based emissions reduction goals. The commission also recommended the development of community impact metrics to inform the development of sequestration strategies and to evaluate trade-offs of those strategies. The commission advised that the metrics include effects on jobs, local economies, public health, and access to programs (OGWC 2021).

The state's housing and land-use law reforms discussed above also will help the state protect natural and working lands from conversion to development. As discussed above, because Oregon's land-use system authorizes cities to expand their urban growth boundaries when more land is needed to house growing populations, pre-2019 local regulatory requirements that most residential land be dedicated to single-unit housing with one or more off-street parking space per housing unit contributed to the expansion of urban areas and conversion of natural and working lands (LeDuc et al. 2000, Manville and Pinski 2020). The Climate-Friendly and Equitable Communities rules discussed above also encourage and require cities in the state's eight metropolitan areas to adopt and enforce land-use plans and regulations that will limit conversion of natural and working lands by increasing density in existing urban areas and preventing sprawl.

Through these actions, Oregon remains a national leader in its use of state and local land-use laws to limit emissions and encourage carbon sequestration by preventing urban sprawl. However, as discussed above, the housing and land-use law reforms and Climate-Friendly and Equitable Communities rules are unlikely to result in sufficient changes in development patterns within the timeframe needed to support achievement of Oregon's 2035 targets. Additionally, incorporation of climate considerations into the statewide planning goals and their implementing regulations provides a significant but unrealized opportunity to better align Oregon land-use law and public and private land-use actions with the state's climate goals.

Reducing Community Vulnerability to Climate-Related Natural Hazards

Local zoning and other local lawmaking authorities provide powerful tools to increase community resilience to climate-related natural hazards (Adams-Schoen 2018, Sullivan 2020b). Oregon has partially utilized this potential. In 2021, Oregon released its updated Climate Change Adaptation Framework, which provides guidance to state agencies in implementing strategic, integrated, and equitable responses to climate change (DLCD 2021). The framework includes recommended strategic responses in six sectors: economy, natural world, built environment and infrastructure, public health, cultural heritage, and social systems. These strategies draw on a variety of state agency tools and legal authorities, and their implementation intentionally requires multiple agencies. Several strategies recognize the link between the state's land-use system and its capacity to respond and adapt to climate change.

The framework identifies two land-use strategies for creating equitable and livable communities. First, the framework suggests that state agencies develop guidance to support communities in integrating climate change and equity into land-use planning. Recommendations include supporting the integration of climate science; providing technical and funding capacity to support consideration of resilience, mitigation, and sequestration in plan adoption and amendment; developing decision-support tools that prioritize equity; and providing guidance on addressing urban heat islands with strategies that have multiple benefits, including increasing the number and size of green spaces and number of urban trees. The Department of Land Conservation and Development and the Department of Geology and Mineral Industries already provide some of these resources (DLCD 2012, 2019b; DLCD and DOGAMI 2019). Second, the framework recommends that the state evaluate the ability of the state land-use planning goals to address climate change and climate equity. DLCD and other state agencies will publish a status update on implementation of the framework in late 2022 or early 2023. The framework is not legally enforceable, however.

Oregon's new Climate-Friendly Area rules include a legally enforceable requirement that cities and certain other urbanized areas submit to the Department of Land Conservation and Development a report on potential climate-friendly areas within their jurisdiction (Oregon Administrative Rule 660-012-0315(4)(f)). The report must include plans to achieve fair and equitable housing outcomes within the potential climate-friendly areas and identify actions to mitigate or avoid potential involuntary displacement of current residents. The department assists local governments in analyzing spatial and housing equity and identifying mitigation strategies (DLCD 2022a).

Strategies to address the resilience of built infrastructure also draw on the land-use system. Land-use centered strategies include encouraging communities—through education and the development of model zoning ordinances and other decision-support tools—to avoid development in areas at high risk of natural hazards, supporting communities in adopting optional provisions in Oregon's model building code that mitigate wildfire risk in the wildland-urban interface, and developing options to relocate infrastructure in vulnerable areas. Although many of these strategies focus on protecting existing buildings and infrastructure from climate impacts, whether through building code requirements or bolstering insurance, strategies also include actions to move development out of high-risk areas. The framework includes other strategies that are not framed as land-use strategies but are closely linked to tools in the land-use system. Examples include promoting green infrastructure and preserving natural lands.

Although the framework provides guidance that may help communities increase their resilience to climate-related natural hazards, the state has not fully utilized existing land-use policies and laws to

facilitate robust climate adaptation. As hazard mitigation specialists and planners recognize, helping local governments counter the social, economic, and political pressure to develop in hazardous areas is essential to increasing resilience (Adams-Schoen 2018).

In Oregon, as in most states, local land-use laws related to hazard mitigation tend to focus on increasing the resilience of individual buildings. But development in hazardous areas increases community vulnerability even when the development incorporates building-level resilience strategies, such as those required by the National Flood Insurance Program's minimum floodplain management standards. Even when the structures are resilient, the risks of residing in hazardous areas are especially high for low-income and historically marginalized populations (Adams-Schoen 2023). For example, in communities participating in the National Flood Insurance Program, low-income and minority residents and renters continue to bear disproportionately high burdens post-disaster, including higher rates of job loss, displacement, and mortality and longer-term social and economic disruption (Adams-Schoen 2018, Rice Kinder Institute for Urban Research 2018). Local laws that focus on individual buildings do not promote land uses that increase or retain risk-mitigating features of undeveloped or less intensively developed land.

In summary, Oregon's land-use system, with its foundation of statewide land-use planning goals, provides a pathway to ensure that the state's land uses are responsive to climate change. Oregon has undertaken innovative land-use law reform that partially integrates the state's climate goals and land-use laws. Although Oregon is a national leader in many aspects of sustainable land use, full integration of climate science and equity considerations into state and local land-use plans and actions would better align Oregon's land-use system with the current and foreseeable effects of climate change.

Acknowledgments

The authors would like to thank the University of Oregon's Environment Initiative Seed Funding Program for financial support and University of Oregon School of Law Environmental & Natural Resources Law Center student fellows Savannah Bogard, Roses Laughlin, Todd Newmister, and Victoria Whalen for research assistance.

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Public Health

Evidence steadily accrues that climate change has profound and compounded effects on human health and health care systems, and that these effects are not distributed equitably (Romanello et al. 2022). For example, as detailed in the fifth Oregon Climate Assessment (Ho et al. 2021) and in *Extreme Temperatures* (this volume), heat causes more deaths in the United States than any other weather-related source of mortality. Exposure of infants and children to high temperatures can be particularly insidious because it not only has direct physiological and mental consequences but increases the likelihood of economic disadvantage, malnourishment, and exposure to conflict, which can affect long-term physical health and exacerbate trauma and tendencies toward violence later in life (Miles-Novelo and Anderson 2019, Montes et al. 2021). Extreme temperatures, both hot and cold, were associated with excess deaths from cardiovascular causes, ischemic heart disease, stroke, and heart failure around the world (Alahmad et al. 2023). Furthermore, in the United States, extreme hot and cold were associated with increases in the number of tweets on Twitter, the social media platform, that contained hate speech (Stechemesser et al. 2022).

As demonstrated in *Wildfire* and *The Economic Implications of Climate Change for Oregon* (this volume), the physical and mental effects of wildfire smoke also are extensive and cascade to other sectors. The three contributions to this *Public Health* section focus on the effects of wildfire smoke on human health and the capacity of heath care systems. Across the western United States, the number of days on which wildfire smoke is present and the concentration of fine particulate matter ($PM_{2.5}$) on those days is increasing (Liu et al. 2016). As much as 50 percent of $PM_{2.5}$ emissions in some areas now comes from wildfire smoke (Burke et al. 2021). Even short-term exposure to elevated levels of concentrations of $PM_{2.5}$ can affect health, attention, and behavior (Cleland et al. 2022, Jones 2022).

Rohlman and colleagues begin this section by synthesizing recent research on the composition and toxicity of wildfire smoke and its effects on health of the general population. They also review new insights on the impacts of wildfire smoke on infant health.

As Kalashnikov explains in the second contribution to this section, as wildfire smoke becomes more prevalent, levels of $PM_{2.5}$ and surface ozone increasingly are high on the same days during summer. Concurrent exposure to multiple air pollutants can exacerbate effects on human health and behavior. For example, short-term exposure to $PM_{2.5}$ and surface-level ozone has been associated with an increase in violent crime in the United States (Burkhardt et al. 2019).

In the third part of this section, Chapman and colleagues report results of their research on the likelihood that a major wildfire season will increase respiratory hospitalizations in Oregon to the extent that a hospital has difficulty managing other patient needs. They highlight that wildfires may be creating a seasonal surge in health care demand analogous to traditional winter influenza seasons.

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Composition of Wildfire Smoke and Health Risks

Diana Rohlman, Samuel Attridge, Kelly O'Malley, and Kim A. Anderson

Introduction

In the western United States, the number of large wildfires (those that burn over 1000 acres [405 ha]) has been increasing since 2010. In 2020 alone, wildfires burned over six million acres (2.43 million ha) in California, Oregon, and Washington (NIFC 2018). These fires resulted in historically poor air quality as measured by the Air Quality Index (Figure 1), with many cities recording hazardous air quality levels (ODEQ 2021b). In Oregon, data from 2010 through 2020 show that smoke from wildfires has substantially affected air quality, with the number of days on which air quality is unhealthy for sensitive groups or worse (orange and above on the Air Quality Index; Figure 1) increasing 24-fold in Bend and nine-fold in Klamath Falls (ODEQ 2021b). In Portland, where air monitoring began in 1985, there never had been a day on which air quality was unhealthy for sensitive groups until 2015. However, during the next five years, Portland recorded an average of 4.6 days per year on which air quality was unhealthy for sensitive groups or worse (ODEQ 2021b). Given the recent trend towards a greater number of days with wildfire smoke, and the increasing size of wildfires (Kenward et al. 2016, ODEQ 2021b), the impact of wildfire smoke on human health is likely to increase.

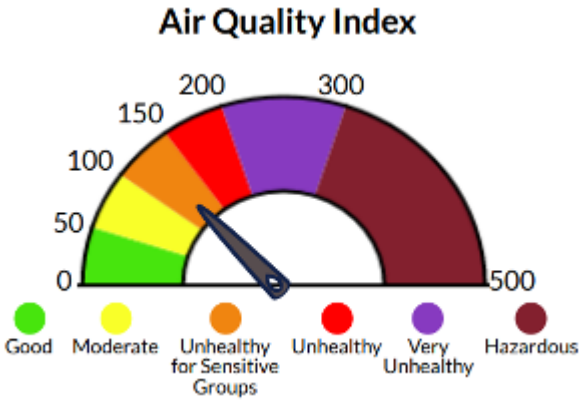

Figure 1. The Air Now Air Quality Index (AQI). Source: www.airnow.gov/aqi/aqi-basics/.

There are decades of research on the health effects associated with exposure to particulate matter (PM), a main component of wildfire smoke. However, reduction of remaining uncertainties could better guide communication of information about wildfire-smoke exposure to protect public health. These uncertainties include the composition and toxicity of smoke, the health effects of repeated high exposures over many days, effects in subsequent years of prolonged exposure to smoke from a single wildfire, effects of repeated exposures to wildfire smoke over multiple fire seasons, and whether smoke from wildfires that burn through the wildland-urban interface (the area where the built and natural environment meet) and less-developed areas have different composition or toxicity and associated health hazards.

Here, we provide an overview of recent research on the composition and toxicity of wildfire smoke, and address effects on health of the general population. We also present a synopsis of emerging research on the impacts of wildfire smoke on infant health, with an emphasis on fires in the wildand-urban interface. Occupational risks, particularly to firefighters and other outdoor workers who experience greater smoke exposure, are substantial (Navarro 2020, Rice et al. 2021) but beyond our scope. For more information on populations potentially at risk of health effects from wildfire smoke, see EPA 2021.

Composition of Wildfire Smoke

Wildfire smoke is a complex mixture of particulates, carbon dioxide, water vapor, carbon monoxide, hydrocarbons and other organic chemicals, nitrogen oxides, and trace minerals. The composition of smoke changes on the basis of the fuel source (Samburova et al. 2016, Rager et al. 2021), fuel conditions, weather, heat of the fire, whether smoke is produced via flaming or smoldering combustion (Urbanski 2013, Seltenrich 2018, Sokolik et al. 2019, Rager et al. 2021), and age of the smoke itself (Liu et al. 2017, O'Dell et al. 2020). The amount of pollutants released following a fire can be estimated with emissions factors. For example, an emission factor can represent the amount of particulate matter released from each kilogram of coal burned (EPA 2022).

Comparing emissions from wildfires that burn under different meteorological and combustion conditions, and potentially in different fuels, means that emission factors differ among fires that burn different built or natural fuels, even in the same region (EPA 2021b). Urbanski et al. (2009) provide a comprehensive review of differences in wildfire emissions among fuel types. Although fuel source affects the composition of smoke (Rager et al. 2021), preliminary evidence from wildfires and controlled burn experiments indicates that fuel source is only one of several factors controlling differences in smoke composition (Urbanski et al. 2009, Hadley et al. 2021, Rager et al. 2021, Sparks and Wagner 2021).

The Smoke Emission Repository Application (SERA) database contains over 12,000 entries that catalogue emission factors from wildfires, prescribed fires, and fires that were ignited in a controlled laboratory setting. Particles less than 2.5 micrometers (μm) in diameter ($PM_{2.5}$) were the most abundant of the 274 pollutants in smoke as reflected in the database (Prichard et al. 2020). Of the hundreds of individual smoke components, $PM_{2.5}$ is the greatest concern to public health (EPA 2021a) because the fine particles can advance deep into the lungs, enter the blood, and affect other organs. Although a large body of knowledge on the health effects of particulate matter (PM) exists, gaps remain in understanding of smoke composition, toxicity, and associated health outcomes, especially in association with wildfires that occur in the wildland-urban interface (Reid et al. 2016, Black et al. 2017, Cascio 2018). Here, we addresses three components of wildfire smoke: particulate matter, volatile and semi-volatile compounds, and gases.

Particulate Matter

Wildfires were estimated to account for up to 25 percent of $PM_{2.5}$ emissions across the United States, and up to 50 percent of $PM_{2.5}$ emissions in the western United States, during the past decade (Burke et al. 2021). Research on wildfire smoke primarily has focused on $PM_{2.5}$ (G. Chen et al. 2021, Zhou et al. 2021) (Table 1), and current wildfire smoke recommendations in Oregon are based on reducing exposure to $PM_{2.5}$ (ODEQ 2021a). However, the breadth and type of materials that may burn, and therefore the composition of smoke, varies between wildland-urban interface fires and wildland fires. Particulate matter, metals, and polycyclic aromatic hydrocarbons (PAHs) have been found at different concentrations in smoke from wildland-urban interface fires relative to other sources (Samburova et al. 2016, Sparks and Wagner 2021). Particles from wildland-urban interface fires had elevated levels of metals and silicon (Sparks and Wagner 2021). Elevated zinc and nickel were associated with submicron particles ($<PM_1$), whereas manganese, tin, copper, and lead were associated with larger particulate matter ($PM_{10\text{-}2.5}$) (Sparks and Wagner 2021).

Polycyclic Aromatic Hydrocarbons

Wildfire smoke also contains volatile organic compounds, including PAHs and gases such as carbon monoxide and carbon dioxide (Liu et al. 2017, Messier et al. 2019, O'Dell et al. 2020, EPA 2021b, Hadley et al. 2021, Rager et al. 2021, Ghetu et al. 2022). The concentration of PAHs in both particle and vapor phases increases during wildfires relative to ambient (no wildfire) conditions (Samburova et al. 2016, Messier et al. 2019, Hadley et al. 2021, Rager et al. 2021, Ghetu et al. 2022). Although $PM_{2.5}$ is the main pollutant of concern, and best characterized in the literature, PAHs also are detected during wildfires. In samples collected during a 2008 wildfire in California, $PM_{2.5}$ contained nearly 50 times more PAHs than coarser particulate matter ($PM_{10-2.5}$), and concentrations of PAHs were greater in particulate matter from wildfire smoke than in particulate matter from ambient air (Wegesser et al. 2009).

Reference	Fire source	Pollutants measured			
		PM	PAHs	Gases	HAPs
Verma et al. 2009	Laboratory	+		+	
Wegesser et al. 2009	Wildfire	+			
Wegesser et al. 2010	Wildfire	+	+		
Franzi et al. 2011	Laboratory	+			
Nakayama Wong et al. 2011	Laboratory	+			
Samburova et al. 2016	Laboratory	+	+		
Liu et al. 2017	Wildfire			+	+
Kim et al. 2019	Laboratory	+		+	
Hadley et al. 2021	Wildfire	+		+	+
Rager et al. 2021	Laboratory	+	+		
Sparks et al. 2021	Wildfire	+			
Ghetu et al. 2022	Wildfire		+		

Table 1. Studies that evaluated wildfire smoke composition. PM, particulate matter; PAHs, polycyclic aromatic hydrocarbons; HAPs, hazardous air pollutants.

PAHs are formed via incomplete combustion and include over 1000 semi-volatile and volatile organic chemicals that each have a minimum of two benzene rings. PAHs include low and high molecular weight compounds in both particle and vapor phases; for example, concentrations of benzo[a]pyrene and naphthalene are highly correlated with that of $PM_{2.5}$ (Hadley et al. 2021). Emission factors of vapor-phase PAHs are higher than those of particle-phase PAHs (Samburova et al. 2016). In one study, per unit mass of consumed fuel, the total mass of PAHs emitted was skewed towards vapor-phase PAHs, mainly due to the release of low molecular weight PAHs such as naphthalene, acenaphthylene, acenaphthene, fluorine, phenanthrene, and anthracene (Samburova et al. 2016). Although prior studies detected lower levels of high molecular weight PAHs in the particle phase in woodsmoke, the emissions from vapor-phase PAHs were not assessed (Hadley et al. 2021). In a separate study, the average outdoor air concentrations of vapor-phase, high molecular weight PAHs were 86 times higher during wildfires than before or after (Ghetu et al. 2022). Twelve unique high molecular weight PAHs have been detected during wildfires (Ghetu et al. 2022). The majority were only detected when the Air Quality Index was greater than 140, irrespective of weather conditions or the primary fuel source (Ghetu et al. 2022).

Gases

In the western United States, over 80 trace gases were characterized during wildfire smoke events, and their concentrations were higher during fires than under ambient conditions (Liu et al. 2017). Gases often emitted from active wildfires include carbon monoxide, carbon dioxide, and formaldehyde (Verma et al. 2009, Liu et al. 2017, Prichard et al. 2020). The Smoke Emissions

Repository Application database includes records on specific gases, including greenhouse gases such as carbon dioxide (Prichard et al. 2020).

In California, levels of carbon monoxide significantly increased during wildfires ($p < 0.001$), although the average (± standard error) concentration during wildfires, 4.77 ± 0.22 ppm, remained below the 8-hour National Ambient Air Quality Standard of 9 ppm (Meo et al. 2021, EPA 2022). In laboratory experiments, wildfire smoke had lower levels of carbon monoxide than woodsmoke, which was attributed to the more efficient wildfire combustion process that emits carbon as carbon dioxide (Hadley et al. 2021). Despite this concentration difference, carbon monoxide emissions from wildfires remain a concern. Gas emissions in fresh smoke plumes (<20 min old) from wildfires were dominated by carbon dioxide, followed by carbon monoxide (Liu et al. 2017).

Other Components

Levels of acrolein, benzene, ammonium, nitrate, chloride, and sulfate were greater in wildfire smoke plumes than in ambient air, although the composition of wildfire smoke plumes shifted rapidly as the smoke aged (Liu et al. 2017, O'Dell et al. 2020). N-alkanes, methoxyphenols, levoglucosan, inorganic elements, metals, and ionic constituents were also detected in smoke generated during laboratory experiments (Rager et al. 2021).

Toxicity of Wildfire Smoke

In a laboratory, toxicity can be assessed via a variety of endpoints, and is used to better understand potential adverse impacts in biological systems outside the laboratory. In laboratory experiments, wildfire smoke samples from different fuel sources had different toxicity (Rager et al. 2021). Toxicity assays may not directly translate to human health. Regardless, however, they inform research on public health. We offer a brief overview of wildfire smoke-associated toxicity to clarify current research on toxicity of wildfire smoke mixtures.

In some cases, toxicity of smoke from different fuel types (e.g., peat versus pine) is associated with mixtures, suggesting potential interactions among chemicals that lead to toxicity, rather than with individual chemicals in isolation (Rager et al. 2021). For example, mixtures of inorganic and ionic constituents induced greater pulmonary toxicity than either set of constituents, yet mixtures with lower levels of methoxyphenols had greater toxicity than mixtures with high levels (Rager et al. 2021). The relative contributions of non-particulate constituents to wildfire smoke composition and overall toxicity are less well characterized (Black et al. 2017). As described below, toxicity varies among components of wildfire smoke.

Particulate Matter

Toxicity associated with particulate matter has been extensively documented (Anderson et al. 2012, EPA 2019). Although PM alone can predict toxicity, the type of PM can also inform toxicity predictions (Park et al. 2018). Additionally, the composition of wildfire smoke changes as it ages (Liu et al. 2017). Smoke from smoldering material has a higher concentration of PM than smoke from flaming material (Kim et al. 2019). Nevertheless, compositional changes may affect toxicity; despite its lower PM, smoke from flaming material had greater toxicity in a mouse lung model (Kim et al. 2019). Smoke from smoldering material induces a greater irritant response in vertebrates than smoke from flaming material (Martin et al. 2021).

Several laboratory studies have compared the toxicity of wildfire-associated PM and ambient PM. Mice treated with PM samples from a wildfire via intratracheal instillation had fewer macrophages and more neutrophils in bronchoalveolar lavage than control mice (Wegesser et al. 2009). The decrease in macrophages was more pronounced than in mice treated with the same dose of PM from ambient air. Similarly, coarse PM ($PM_{10-2.5}$) from wildfires was about four times more toxic to lung macrophages per unit weight basis than coarse PM from ambient air from the same region and season (Franzi et al. 2011). Additional experiments comparing wildfire-associated PM to ambient PM have identified differential gene expression patterns in human bronchial epithelial cells (Nakayama Wong et al. 2011). These studies indicate differences in toxicity between wildfire PM and PM from other sources, such as vehicle exhaust, woodsmoke, and dust (Wegesser et al. 2009; Franzi et al. 2011; Aguilera et al. 2021a, b; Liu et al. 2021).

Polycyclic Aromatic Hydrocarbons

Many particle-phase PAHs have been identified in wildfire smoke, although they are not restricted to wildfires. In laboratory studies of five common wildfire fuel sources, particle-phase benzo[a] pyrene was the major contributor to PAH-related toxicity (Samburova et al. 2016). A laboratory study evaluating 113 particle- and vapor-phase PAHs in wildfire smoke indicated that despite the higher emissions factor of vapor-phase PAHs, the carcinogenic potency of particle-phase PAHs was greater (Samburova et al. 2016).

Gases

Formaldehyde was detected at levels above California Environmental Protection Agency reference exposure levels in fresh smoke (<20 min old), and below reference levels as the smoke aged (O'Dell et al. 2020), leading to concerns that exposure to young smoke, for example by wildland firefighters, would be toxic (O'Dell et al. 2020). Although gas-phase hazardous air pollutants appeared to contribute less to overall health than PM, the contribution was detectable (O'Dell et al. 2020).

Wildfire Smoke and Human Health

Exposure to wildfire smoke can have health effects including mortality (G. Chen et al. 2021), adverse respiratory outcomes (emergency room visits, hospitalizations, asthma) (Kiser et al. 2020, Aguilera et al. 2021a, b), chronic obstructive pulmonary disease), and adverse cardiovascular outcomes (Reid et al. 2016, Black et al. 2017, Cascio 2018, EPA 2021a, b). Effects of wildfire smoke on human health have most often been assessed by modeling or measuring daily exposure to wildfire smoke and via impacts on the health care system, measured by emergency visits or hospitalizations for respiratory-associated symptoms and diseases (Black et al. 2017). Here, we evaluate new research characterizing health effects associated with wildfire smoke in the United States and Canada since 2019. We also focus on prenatal exposure to wildfire smoke and adverse infant health outcomes globally, which is an emerging area of concern.

The way in which exposure was measured (e.g. direct measurement of PM, wildfire-specific PM, wildfire smoke density, smoke plume data) differed among the studies cited below. No one metric has been identified as the most appropriate, yet results are largely consistent among exposure metrics and health outcomes. The use of different exposure metrics to characterize wildfire smoke exposure across epidemiological studies is further discussed in EPA 2021b.

Mortality

There is an established, causal relation between short-term exposure to $PM_{2.5}$ and mortality (EPA 2019). Several studies have identified a positive association between all-cause mortality and exposure to $PM_{2.5}$ from wildfire smoke (Table 2), with 0.62–1.3 percent increases in all-cause mortality following exposure (Doubleday et al. 2020, Matz et al. 2020, G. Chen et al. 2021, Liu et al. 2021). Increased rates of mortality were commonly associated with respiratory- and cardiovascular-associated mortality (Doubleday et al. 2020, Matz et al. 2020, G. Chen et al. 2021, Liu et al. 2021). Mortality was highest among those 65 or older (Doubleday et al. 2020). Furthermore, individuals with lower socioeconomic status had an increased risk of mortality following exposure to $PM_{2.5}$ from wildfire smoke (Doubleday et al. 2020, Liu et al. 2021). Exposure to wildfire smoke-associated $PM_{2.5}$ had a stronger effect on mortality than ambient $PM_{2.5}$ (G. Chen et al. 2021).

Reference	Mortality	Population studied		
		Children	Adults	Adults >65
Casey et al. 2020	null			
Doubleday et al. 2020	+		+	+
Matz et al. 2020	+			
G. Chen et al. 2021	+			
Liu et al. 2021a	+			

Table 2. Association of wildfire smoke exposure with mortality. +, positive association; null, null association.

Respiratory Health

The relation between short- and long-term $PM_{2.5}$ exposure and subsequent impacts on respiratory health likely is causal (Black et al. 2017, EPA 2019). Therefore, evaluations of exposure to wildfire smoke, in which the major component is $PM_{2.5}$, mainly have focused on respiratory-related effects (Table 3). Respiratory hospital admissions of the general population increase during wildfire events (DeFlorio-Barker et al. 2019, Casey et al. 2020, Liebel et al. 2020). Exposure to wildfire smoke is positively associated with exacerbation of asthma among children and adults (Lipner et al. 2019, Stowell et al. 2019, Kiser et al. 2020, Hahn et al. 2021) (Table 3). In a residential population exposed to wildfire smoke, lung function was significantly decreased one year following exposure, and remained low after several years (Orr et al. 2020).

Reference	Mortality	Population studied		
		Children	Adults	Adults >65
DeFlorio-Barker et al. 2019	+			+
Lipner et al. 2019	null	+		
Stowell et al. 2019	+	+	+	-
Casey et al. 2020	+			
Doubleday et al. 2020	+		+	+
Kiser et al. 2020	+			
Leibel et al. 2020	+	+		
Matz et al. 2020	+			
Orr et al. 2020	+		+	+
Yao et al. 2020	+			
Aguilera et al. 2021a	+	+		
Aguilera et al. 2021b	+			
G. Chen et al. 2021	+			
Hahn et al. 2021	+	+	+	+
Haikerwal et al. 2021	+		+	
Liu et al. 2021a	+			
Blando et al. 2022	+	+	+	

Table 3. Association of wildfire smoke exposure with respiratory health. +, positive association; null, null association.

In a time series study across 749 locations,

exposure to wildfire-related $PM_{2.5}$ was associated with increased relative risk of all-cause, cardiovascular, and respiratory mortality (G. Chen et al. 2021). The estimated risk was greater than expected relative to short-term exposure to ambient $PM_{2.5}$ (G. Chen et al. 2021). In Nevada, the association between asthma-related emergency department visits per 5 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ was strongest during wildfire events (Kiser et al. 2020). Because Kiser et al. (2020) limited their analysis to the maximum $PM_{2.5}$ concentration on non-wildfire days, only wildfire days on which $PM_{2.5}$ was similar to non-wildfire days were analyzed. In California, for each 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ associated with wildfire smoke, pediatric (0–19 years of age) respiratory hospitalizations increased by 1.3–10 percent (Aguilera et al. 2021b). By contrast, respiratory hospitalizations increased by 0.67–1.3 percent for each 10 $\mu g\ m^{-3}$ increase in ambient $PM_{2.5}$ (Aguilera et al. 2021b).

Influenza was associated positively with increasing $PM_{2.5}$ levels during wildfire season (Landguth et al. 2020) (Table 4). Additionally, several studies have reported initial evidence of associations between exposure to wildfire smoke and SARS-CoV-2 infections (Curtis et al. 2021, Leifer et al. 2021, Meo et al. 2021, Zhou et al. 2021, Schwarz et al. 2022) and deaths (Curtis 2021, Zhou et al. 2021). For a comprehensive review of the impact of wildfire smoke on respiratory health, refer to Grant et al. (2022).

Reference	Virus and effect			Population studied		
	COVID-19 infection	COVID-19 death	Influenza infection	Children	Adults	Adults >65
Landguth et al. 2020			+			
Leifer et al. 2021	+					
Meo et al. 2021	+	+				
Zhou et al. 2021	+	+				
Schwarz et al. 2022		+				

Table 4. Association of wildfire smoke exposure with viral infections. +, positive association.

Cardiovascular Health

A comprehensive review identified a causal relation between short-term and long-term exposure to $PM_{2.5}$ and cardiovascular effects (EPA 2019). The literature on cardiovascular health following exposure to wildfire smoke supports a positive relation (Table 5) (H. Chen et al. 2021). The impacts of wildfire smoke on cardiovascular health have most often been assessed as a function of ambulance dispatches (Yao et al. 2020), emergency department admissions (Casey et al. 2020, Hahn et al. 2021), hospitalizations (DeFlorio-Barker et al. 2019), and out-of-hospital cardiac events (Jones et al. 2020). Out-of-hospital cardiac arrests are typically excluded from analyses of emergency department and hospital admissions; 70 percent of these events are not admitted due to death occurring on arrival

Reference	Mortality	Population studied		
		Children	Adults	Adults >65
DeFlorio-Barker et al. 2019	+			+
Stowell et al. 2019	null	+	+	-
Casey et al. 2020	null			
Doubleday et al. 2020	+		+	+
Jones et al. 2020	+		+	+
Yao et al. 2020	+			
H. Chen et al. 2021	+			
Hahn et al. 2021	+	+	+	+

Table 5. Association of wildfire smoke exposure with cardiovascular health. +, positive association; -, negative association; null, null association.

or during transport via ambulance (Jones et al. 2020). Out-of-hospital cardiac events increased following exposure to wildfire smoke, and the effect was exacerbated among individuals with lower socioeconomic status (Jones et al. 2020). Asssessed by ambulance dispatches, as $PM_{2.5}$ increased during wildfire season, there was a concurrent increase in adverse cardiovascular outcomes (Yao et al. 2020). Similarly, as the density of wildfire smoke (and therefore the density of $PM_{2.5}$) increased, the risk of all-cause cardiovascular outcomes resulting in emergency department visits increased, with older adults at greater risk (Wettstein et al. 2018). In contrast, DeFlorio-Barker et al. (2019) found no increase in cardiovascular-associated hospitalizations: for each 10 $\mu g\ m^{-3}$ increase in either wildfire or ambient $PM_{2.5}$, the risk of cardiovascular hospitalization was the same.

Cancer

Exposure to wildfire smoke and incidence of cancer is not well studied, and relies solely on toxicological laboratory models and cancer risk assessments. Toxicological studies indicate a variety of mechanisms by which exposure to $PM_{2.5}$ may increase cancer risk (EPA 2019). $PM_{2.5}$ exposure has been linked with lung cancer mortality, and there appears to be a positive association between exposure to $PM_{2.5}$ and lung cancer incidence (EPA 2019). However, no studies have correlated exposure to $PM_{2.5}$ specifically from wildfire smoke and subsequent cancer risk.

Less is known about cancer risk following exposure to PAHs during wildfires, and PAHs infrequently are monitored during wildfires. Exposure to PAHs has been associated with cancer as assessed by cancer risk models (ATSDR 1995). Vapor-phase PAHs are estimated to contribute up to 86 percent of the carcinogenicity attributed to PAHs (Ramírez et al. 2011, Samburova et al. 2017). In a small study that used passive samplers to evaluate concentrations of vapor-phase PAHs in ambient indoor and outdoor air on each of seven days, PAH levels increased during periods of wildfire smoke that were mild as measured with the Hazard Mapping System (Messier et al. 2019). Cancer risk as indicated by concentrations of benzo[a]pyrene (a Group 1 carcinogen) was not significantly different on days with increased wildfire smoke and days with low outdoor smoke inundation (Messier et al. 2019). In a larger study across Washington, Oregon, California, and Idaho, indoor and outdoor exposure to wildfire smoke over seven days increased lifetime cancer risk, yet the estimated risk was below $1x10^{-6}$ at most locations (Ghetu et al. 2020). For reference, a risk of one in a million indicates that there may be one additional case of cancer over 70 years in a population of one million people.

Pregnancy and Birth Outcomes

The current evidence suggests, but is not sufficient to conclude, that ambient exposures to $PM_{2.5}$ affect pregnancy and birth outcomes (EPA 2019). Interpreting results across studies is difficult given the diverse ways in which exposure is assessed, the assessment of covariates related to birth outcomes (such as smoking and prenatal care), and the trimester evaluated (EPA 2019). Since 2019, new studies in the United States, Canada, and Brazil evaluated the association between prenatal exposure to wildfire smoke and adverse infant health outcomes, such as preterm birth (a live singleton birth that occurs before 37 weeks of pregnancy; WHO 2022a) and low birth weight (a singleton that weighs less than 5.5 lb [2,500 g]; WHO 2022b). Fetal development is a highly susceptible time period. Depending on the timing of exposure, prenatal exposure to $PM_{2.5}$—even short-term exposure, such as that during wildfires (Melody et al. 2019)—can be associated with preterm birth (Huynh et al. 2006, Ritz et al. 2007, Yuan et al. 2019) and low birth weight (Stieb et al. 2012, Yuan et al. 2019) (Table 6). The prenatal period also is sensitive given that the alveolar

ventilation rate increases during pregnancy (Hackley et al. 2007), resulting in a potentially larger dose. Individuals born preterm or with low birth weight are more susceptible to adverse respiratory health outcomes in early adulthood (Haikerwal et al. 2021).

We highlight the impact of wildfire smoke exposure in utero on preterm birth and low birth weight while recognizing the limitations within this field of study. A review of prenatal smoke exposure, preterm birth, and low birth weight globally found significant, positive associations (Amjad et al. 2021). Prenatal exposure to wildfire smoke was first characterized in 2012, when PM_{10} concentrations from wildfires were modeled across California (Holstius et al. 2012). The mean birth weight of infants exposed in utero during any trimester was 6.1 g lower than that of infants that were not exposed; the decrease was greatest when the fetus was exposed in the second trimester (Holstius et al. 2012). Subsequent studies also found positive associations between prenatal smoke exposure and low birth weight (Abdo et al. 2019, Mccoy and Zhao 2021, Requia et al. 2022a).

Reference	Infant health outcomes	
	Preterm birth	Low birth weight
Abdo et al. 2019	+	null
Heft-Neal et al. 2022	+	
Requia et al. 2022a	+	
Requia et al. 2022b		+

Table 6. Association of wildfire smoke exposure with infant (0-1 years of age) human health outcomes. +, positive association; null, null association.

Similarly, the timing of exposure to wildfire smoke is associated with the magnitude of incidence of preterm birth. Although wildfire smoke exposure at any time during pregnancy is associated with preterm birth, the risk was greatest when exposure occurred during the second trimester (Abdo et al. 2019, Heft-Neal et al. 2022, Requia et al. 2022b). Among more than three million births in California from 2006 through 2011, for each additional day of wildfire smoke over the course of the pregnancy, the risk of preterm birth increased by 0.49 percent (Heft-Neal et al. 2022). However, the effect was greatest when the smoke exposure occurred during the second trimester, and the model indicated that 3–4 percent of preterm births in California were attributable to wildfire smoke exposure (Heft-Neal et al. 2022). Additional adverse outcomes that require more research include associations between wildfire smoke exposure and the outcomes of small for gestational age and infant mortality (Amjad et al. 2021). Exposure to wildfire smoke also may be associated with gestational diabetes and gestational hypertension (Abdo et al. 2019, H. Chen et al. 2021).

Conclusions

As wildfire seasons in Oregon become longer, and large fires become more frequent (ODEQ 2021b), human exposure to wildfire smoke also becomes more frequent. Such exposure is anticipated to lead to a range of health effects including adverse respiratory health outcomes (Reid and Maestas 2019). Wildfire smoke is a complex mixture, and the concentrations of many of its chemical components are greater than in ambient air. The predominant pollutant emitted from wildfires is $PM_{2.5}$, with models indicating that emissions from wildfires account for up to 50 percent of $PM_{2.5}$ in the western United States (Burke et al. 2021). Exposure to particulate matter is associated with mortality, respiratory health, adverse birth outcomes, and cardiovascular health (Feng et al. 2016). Other smoke components, in either the particle or the vapor phase, may also contribute to adverse health effects, although their relative contributions are poorly characterized. A better understanding of the toxicity of all pollutants and their potential interactions in wildfire smoke may inform the management of fine particles beyond the current regulatory standard, which is based on PM mass alone.

Acknowledgments

This work was supported by the National Institute of Environmental Health Sciences (P30 ES030287, P42 ES016465). S.A. was partially supported by the Oregon State University Honors College DeLoach Work Scholarship.

We gratefully acknowledge James Markwiese and Alan Thornhill (Pacific Ecological Systems Division, Center for Public Health and Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency) for sharing their time and expertise.

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Compounded Health Effects of Fine Particulate Matter and Surface Ozone

Dmitri Kalashnikov

Exposure to fine particulate matter ($PM_{2.5}$) and surface ozone are associated with human health impacts including impaired cardiac and respiratory functions, and with increased chances of hospitalization and premature mortality (www.epa.gov/air-research/research-health-effects-air-pollution). High levels of $PM_{2.5}$ and surface ozone pollution are increasingly co-occurring on the same days during summer across many parts of Oregon (Figure 1a) (Kalashnikov et al. 2022).

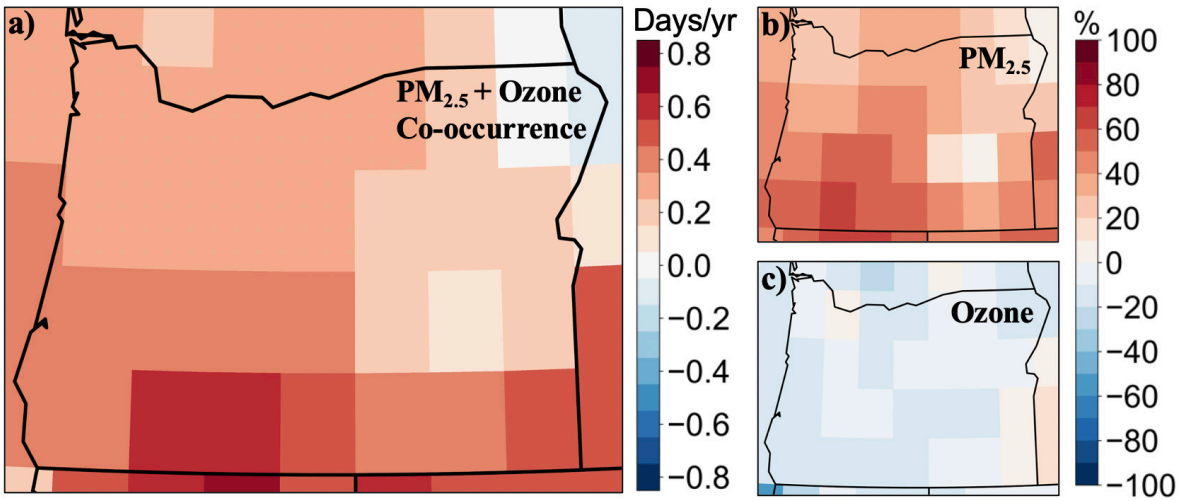

Figure 1. (a) 2001–2020 trends in the number of days per year (July, August, and September) with co-occurring high values of $PM_{2.5}$ and ozone. Co-occurrences are defined as values of both pollutants that exceed their local 90th percentile daily concentrations in the given year. Trends in the annual percentage of (b) $PM_{2.5}$ extremes and (c) ozone extremes occurring in each grid cell during July, August, and September relative to the rest of the year. Maps produced with air quality observations from the U.S. Environmental Protection Agency and adapted from Kalashnikov et al. 2022.

There is some indication that simultaneous exposure to multiple harmful air pollutants can have disproportionately higher impacts on human health than exposure to individual pollutants (Reid et al. 2019, Siddika et al. 2019).

The observed trends in co-occurrence of $PM_{2.5}$ and ozone can be linked to increasing prevalence of $PM_{2.5}$ from wildfire smoke across the region (Figure 1b), which coincides with ozone levels that are typically high during summer due to warm temperatures and abundant sunshine. Furthermore, wildfire smoke can lead to greater ozone concentrations when it mixes with urban pollution, and ozone levels are often elevated on smoky days during summer in cities in the western United States (Brey and Fischer 2016, Gong et al. 2017, Buysse et al. 2019). During the first decade of the twenty-first century, when large wildfires were less common, $PM_{2.5}$ concentrations in much of the western United States, including Oregon, were highest during the cool season, when stagnant air conditions and atmospheric inversions are prevalent (Figure 2a) (Hou and Wu 2016). The difference in timing of annual peak concentrations of $PM_{2.5}$ and ozone limited the chances of these two air pollutants co-occurring, at high concentrations, on the same days. Wildfires, therefore, are a mechanism of the observed shift in the timing of highest $PM_{2.5}$ concentrations toward summer rather than winter (Figure 2b), which increases the risk of co-occurring $PM_{2.5}$ and ozone and their adverse health impacts on Oregon's population.

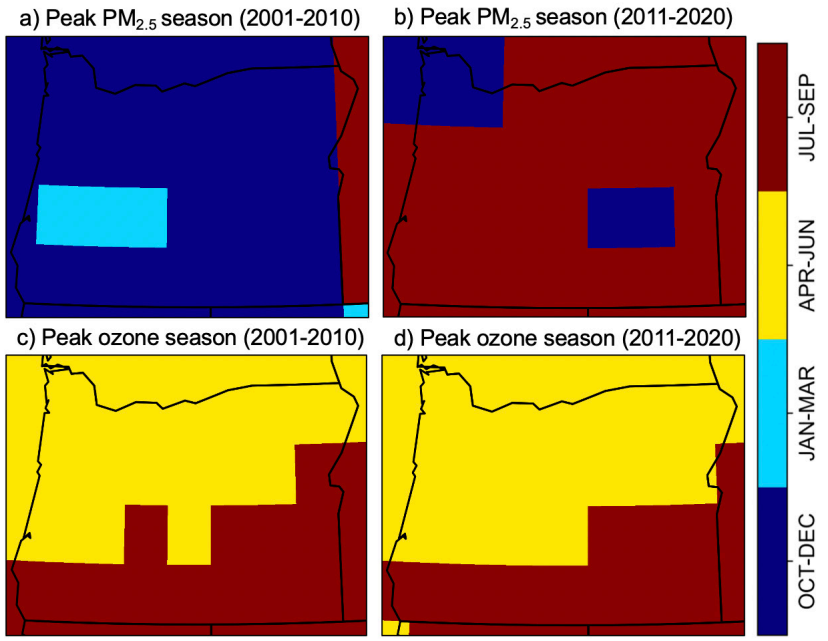

Figure 2. Seasons of peak average concentrations of PM2.5 (top) and ozone (bottom) from 2001–2010 (left) and 2011–2020 (right) in each grid cell. Maps produced with air quality observations from the U.S. Environmental Protection Agency and adapted from Kalashnikov et al. 2022.

As the projected risks of heatwaves and wildfires in Oregon and the rest of the western United States increase (Hicke et al. 2022), the risk of simultaneous exposure to multiple health hazards is also likely to increase. Certain populations, including children, pregnant women, elderly, and people with pre-existing heart or lung conditions, are likely to be more vulnerable to these climate-related health hazards (www.epa.gov/air-research/research-health-effects-air-pollution). Additional factors such as limited access to health care and disaster preparedness resources, and high baseline levels of pollution and other environmental risks faced by many low-income communities, indigenous peoples, and communities of color living in neighborhoods shaped by discriminatory housing policies, also contribute to higher vulnerability and lower adaptive capacity to climate-related health risks (Gamble et al. 2016).

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Fires, Respiratory Hospitalizations, and Capacity Issues

Kyle A. Chapman, Adelaide E. Clark, Kerry L. Farris, and Sarah Fitzpatrick

Wildfires and Climate Change

An estimated 6 million km^2 (2.3 million mi^2) worldwide, and 90,000 km^2 (34,750 mi^2) in the United States, burn annually due to wildfire (Mouillot and Field 2005, Koplitz et al. 2018, Ye et al. 2021). The total area burned in the western United States doubled from 1984 through 2015. In 2017, over 28,000 km^2 (10,800 mi^2) burned in the western United States (Abatzoglou and Williams 2016, Orr et al. 2020). Despite mitigation efforts that improved overall air quality across the United States, wildfires have increased emissions of numerous pollutants, including particulate matter (PM) (Black et al. 2017). $PM_{2.5}$ (PM less than 2.5 microns in aerodynamic diameter) is considered an essential component of wildfire smoke that degrades regional and local air quality during wildfires (Williamson et al. 2016, Lassman et al. 2017, Sheldon and Sankaran 2017, Alonso-Blanco et al. 2018, Larsen et al. 2018, McClure and Jaffe 2018, Requia et al. 2021, Ye et al. 2021). Fifty-two percent of annual $PM_{2.5}$ exceedances of the U.S. National Ambient Air Quality Standard occur in summer during wildfire season, and 26 percent of summer particulate matter in the western United States is attributed to wildfires (Kaulfus et al. 2017, Ridley et al. 2018). These emissions, including $PM_{2.5}$ concentrations, are expected to escalate due in part to climate change, especially in the western United States, where prevalence of wildfires will increase, wildfire seasons will become longer, and larger areas will burn (Flannigan et al. 2000, Kinney 2008, Abatzoglou and Williams 2016, Reid et al. 2016, Black et al. 2017, Cascio 2018). $PM_{2.5}$ exposures due to smoke are expected to increase 160 percent in the next 30–40 years (Liu et al. 2016), with the burned area in the Pacific Northwest expected to increase 80 percent by 2050 (Orr et al. 2020). Additionally, because particulates in wildfire smoke are mainly $PM_{2.5}$ (not larger particles), which settle out of the atmosphere slowly and therefore can disperse far from their sources, there is an increased chance of exposures to $PM_{2.5}$ downwind from wildfires (Makkonen et al. 2010, Urbanski 2013, Black et al. 2017, Ye et al. 2021).

Exposures to Wildfire Smoke

Exposure to wildfire-related emission sources increasingly has become a public health concern in the Pacific Northwest, not only because it presents direct human health effects but because it increases health care use (Makkonen et al. 2010, Dohrenwend et al. 2013, Urbanski 2013, Kochi et al. 2016, Cascio 2018, Hutchinson et al. 2018, Nelson 2020, Ye et al. 2021). Short-term exposures to high concentrations of $PM_{2.5}$ from wildfires can trigger adverse health outcomes including asthma, heart attacks, stroke, and decreased lung function; 339,000 premature deaths per year are attributed to these exposures (Kinney 2008, Reid et al. 2016, Borchers Arriagada et al. 2019, Stowell et al. 2019, Matz et al. 2020, Requia et al. 2021, Ye et al. 2021). Exposure to wildfire smoke may result in more-severe adverse health effects than exposure to similar levels of more-traditional sources of $PM_{2.5}$, such as diesel emission (Borchers Arriagada et al. 2019). As climate change exacerbates wildfire prevalence, an estimated tens of millions of people in the United States will be exposed to smoke at least once per 20 years by the middle to late twenty-first century (Mills et al. 2018).

Patients seeking treatment for a variety of respiratory diseases have a major impact on healthcare (including emergency room visits, hospital admissions, and outpatient visits) (Künzli et al. 2006, Viswanathan et al. 2006, Johnston et al. 2007, Delfino et al. 2009, Tham et al. 2009, Henderson et al. 2011, Dohrenwend et al. 2013, Dennekamp et al. 2015, Black et al. 2017, Liu et al. 2017, Reid et

al. 2019). Many of these studies focused on PM_{10} instead of $PM_{2.5}$. However, $PM_{2.5}$ is more strongly associated with human health effects, meaning previous links between $PM_{2.5}$ and respiratory diseases may have been underestimated (Black et al. 2017).

Health Care Systems and Surge Capacity

Smoke exposures pose substantial risks to both individuals and community services. Hospitals and public health organizations routinely plan to address medical surge capacity, or a system's ability to provide sufficient medical evaluation and care during periods of time that exceed the capabilities of the normal medical infrastructure of an affected community (PHE.gov). When health care organizations experience a marked increase in number of patients (a surge), there can be shortages of resources required for patient care. When a surge is due to a specific type of disease or complication, the ability of a health care organization to treat individuals with other conditions can be adversely affected. The COVID-19 pandemic surge exemplified this risk, with cancellation of surgeries, shifting of resources to triage, and increasing responsibilities of intensive care unit staff (Kerlin et al. 2021).

Such problems are compounded by increases in patient efficiency over the past decade. For example, hospitals today often operate at an average of 80 percent capacity and attempt to reduce the need for additional beds in an effort to save money and provide higher quality care (Litvak and Bisognano 2011). Hospitals in the western United States often plan for medical surges related to wildfires. However, those plans generally are limited to service of acute conditions resulting from direct exposure to wildfire, such as treatment of burns, immediate surgery, and life-sustaining ventilation.

Hospitals may also experience an increase in burden related to aggravation of chronic illness and less life-threatening respiratory conditions. Similar to the burdens on hospitals during COVID-19 waves, during wildfires and related smoke exposures, patients with less severe conditions may not receive needed care or hospitals may have lower capacity for proper care of those patients. Additionally, wildfires now require increased staff capacity and resource allocation during traditionally lower periods of demand. In the past, hospital systems prepared for increased usage and demand on respiratory care during winter. However, in summer, when rates of respiratory illness typically decrease, the risk of wildfires dramatically increases.

Research Aim

The relations between wildfires and health care systems' ability to handle such events are unknown, and must be better understood before action can be taken to improve health care systems' response to wildfires. We used data on $PM_{2.5}$ concentrations to predict the likelihood that a hospital will exceed capacity. We sought to determine the degree to which a major wildfire season, as occurred in 2018, is associated with respiratory hospitalizations that may compromise a hospital's ability to manage patient needs.

Data and Methods

We used air quality data from the Oregon Department of Environmental Quality (DEQ 2020) and electronic medical records from Asante Hospitals in southern Oregon. The study was reviewed by Asante's Southern Oregon Institutional Review Board (SO-IRB) and the Oregon Institute of Technology Institutional Review Board and deemed exempt.

Location and Air Quality Data Acquisition

We obtained data on $PM_{2.5}$ concentrations from the Oregon DEQ air monitoring network for criteria pollutants. The DEQ maintains over 40 $PM_{2.5}$ monitors in the state of Oregon, with six monitors located in the Rogue Valley (Figure 1). These stations are located in Medford (42.3315, -122.8803), Grants Pass (42.4342, -123.3485), Ashland (42.1941, -122.7086), Shady Cove (42.6625, -122.8095), Provolt Seed Orchard (in Grants Pass) (42.2886, -123.2308), and Cave Junction (42.1173, -123.6748). These monitors measure $PM_{2.5}$ continuously with R & P Partisol®-Plus 2025 PM-2.5 Seq. with VSCC™ nephelometers, meeting U.S. Environmental Protection Agency Method 145 (2020). Data are collected and reported by the DEQ as hourly averages. To estimate mean daily $PM_{2.5}$ concentrations, we averaged the 24 hourly values provided by the DEQ for each calendar day at each station.

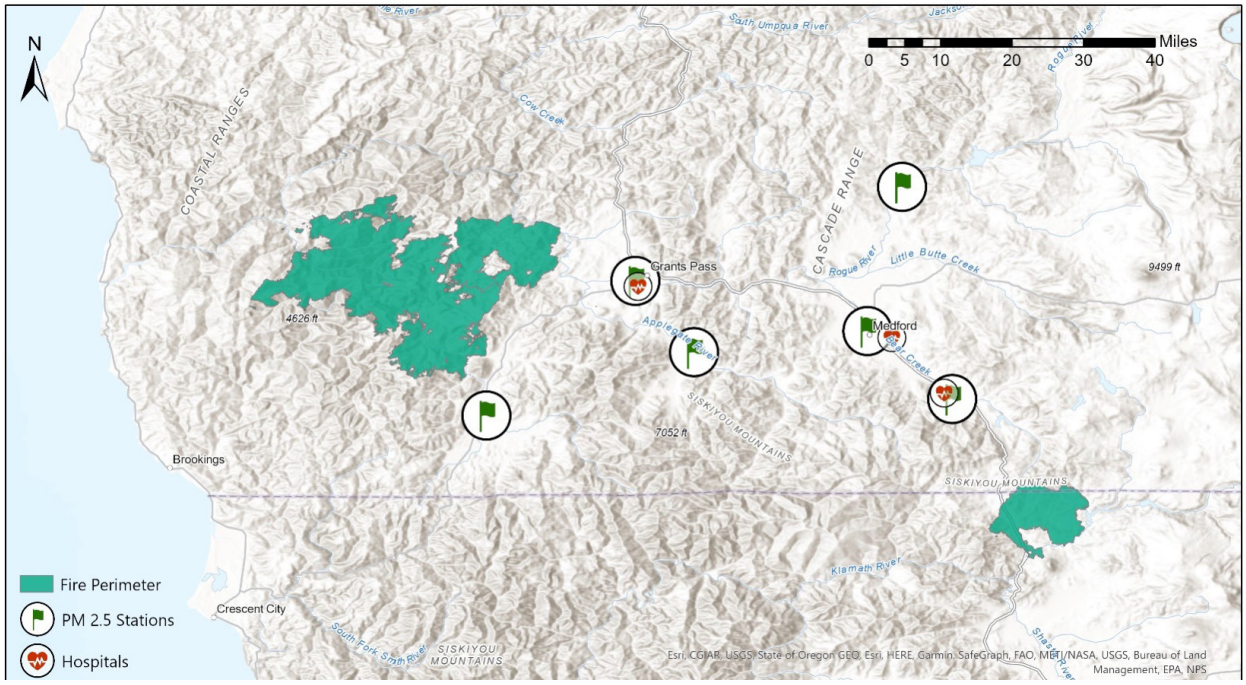

Figure 1. Six Oregon Department of Environmental Quality air monitor locations in the Rogue Valley (green flags); Asante Hospital locations in Medford, Ashland, and Grants Pass (red hearts); and perimeters of the Klondike, Taylor Creek, and Klamathon fires (green shading), which were the major sources of elevated $PM_{2.5}$ concentrations in 2018. Map created by Eleanor Kenyon, Oregon Institute of Technology.

Electronic Medical Records

We obtained patient data (n=354; 159 male, 195 female) through a partnership with Asante Hospitals and analyzed the data with previously published methods (Wettstein et al. 2018). All electronic medical records were de-identified by hospital staff before release to the research team. Medical records included hospital admittance location, admission date, discharge date, age, sex, residential zip code, diagnostic ICD 10 code, and insurance type. Our analysis included data from three Southern Oregon hospitals (Figure 1): Rogue Regional Medical Center (Medford; n=154), Three Rivers Medical Center (Grants Pass; n=167), and Asante Ashland Community Hospital (Ashland; n=33). Patients ranged from 1 to 98 years of age. Patients included in this study were admitted to one of the participating hospitals with a medical condition classified as one of 22 International Classification of Diseases (ICD)-10 codes (Table 1). Only those patients admitted

as in-patient, to the emergency department, or for observation were included. Patients listed as outpatients were excluded. Thirty-nine of the 354 patient encounters were readmits across the three hospitals and another four were treated at an affiliated facility within 90 days of their previous admission under one of the 22 ICD-10 codes (Table 1). The majority of patient encounters at all three hospitals (n=258) were in the emergency department.

Medical condition	Diagnostic code
Chronic obstructive pulmonary disease with acute exacerbation	J44.1
Chronic obstructive pulmonary disease with acute lower respiratory tract infection	J44.0
Asthma	J45.20-22, J45.30-32, J45.40-42, J45.50-52, J45.901, J45.902, J45.909
Emphysema	J43.0-2, J43.8-9

Table 1. Diagnostic codes (ICD-10) and related respiratory medical conditions used in this study.

Data Analysis

We estimated daily regional hospital burden (the dependent variable) by summing the number of respiratory patients admitted to each of the three hospitals from 1 July through 30 September, 2018. These dates corresponded to elevated $PM_{2.5}$ concentrations from wildfires. We considered the daily respiratory patient burden excessive if it surpassed the 80th percentile of the observed 92-day distribution. Excessive burden days were coded 1, whereas daily burdens below the 80th percentile were coded 0. We averaged daily $PM_{2.5}$ concentrations (the independent variable) across the three stations closest to each hospital (Ashland, Medford, and Provolt Seed Orchard). We then used a generalized linear model with a binomial error structure, implemented in program R (R Core Team 2020), to estimate the probability of exceeding respiratory hospital burden as a function of same-day and 3-, 5-, 7-, 9-, and 11-day $PM_{2.5}$ concentration averages.

Results

Effect of Fires on Regional Particulate Matter

In 2018, smoke from wildfires affected the Rogue Valley for approximately 92 days (Figure 2). Most of the smoke was generated by the Klondike, Taylor Creek, and Klamathon fires, which burned about 1046 km^2 (404 mi^2) combined (NIFC 2018). During this period, the average daily $PM_{2.5}$ concentration ranged from 29.6 μg m^{-3} (Grants Pass) to 54.6 μg m^{-3} (Medford) (Table 2). Maximum

2018 fire season (1 July – 30 September)							
Station	Average (μg m^{-3})	Median (μg m^{-3})	Max (μg m^{-3})	Smoke wave days	Unhealthy	Very unhealthy	Hazardous
Ashland	51.4	27.3	244.8	49	29	6	0
Medford	54.6	31.9	264.2	51	32	7	1
Provolt (in Grants Pass)	36.8	18.4	178.2	40	24	1	0
Grants Pass	29.6	11.6	201.2	34	17	1	0
Cave Junction	31.7	15.4	137.0	39	20	0	0
Shady Cove	45.4	23.7	217.7	49	30	2	0

Table 2. Average, median, and maximum daily $PM_{2.5}$ concentration and number of days with or exceeding unhealthy (Air Quality Index red), very unhealthy (Air Quality Index purple), and hazardous (Air Quality Index maroon) concentrations of $PM_{2.5}$.

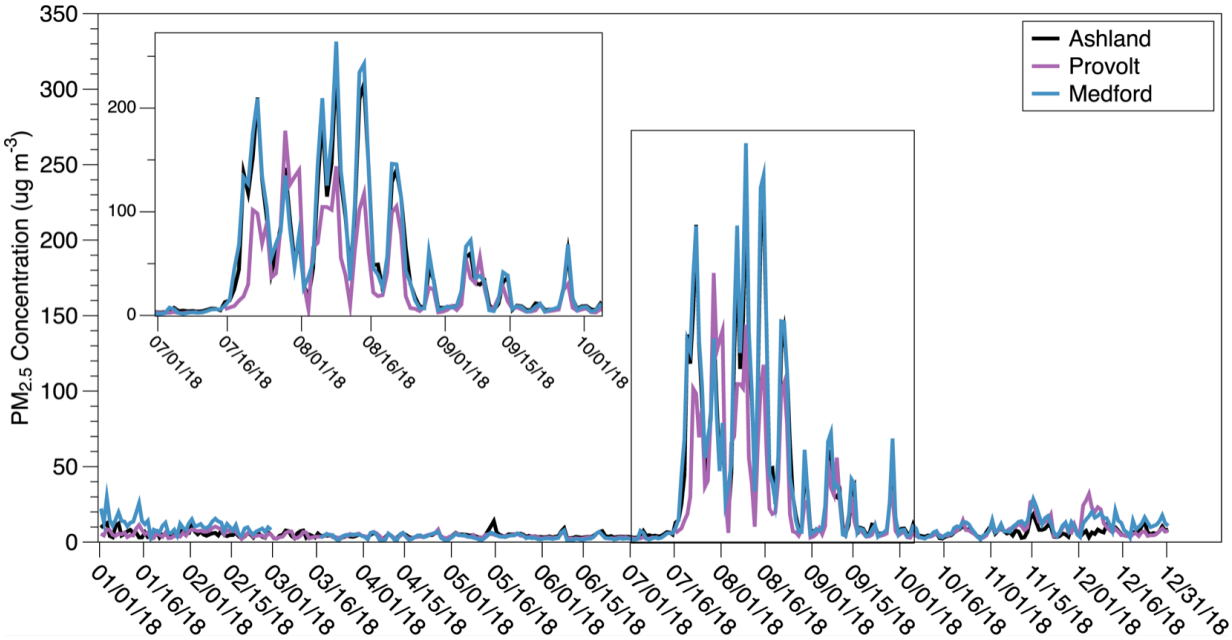

Figure 2. Time series of daily average $PM_{2.5}$ concentrations at Ashland (black), Provolt (purple), and Medford (blue) stations for the year 2018.

observed daily $PM_{2.5}$ concentrations were 137.0 to 264.2 μg m^{-3}. This resulted in 34–51 smoke wave days ($PM_{2.5}$ concentrations >20 μg m^{-3}) (Liu et al., 2017), or 45–67 percent of the 92-day season. Seventeen to 32 days (22–42 percent) of at least unhealthy air quality (U.S. Environmental Protection Agency Air Quality Index [AQI] red, or concentrations >55.5 μg m^{-3}) were observed in the region. One to seven days of very unhealthy air quality (AQI purple, or concentrations >150.5 μg m^{-3}) were also observed. Only one hazardous (AQI maroon, or concentrations >250.5 μg m^{-3}) daily average was observed. However, as many as 81 hazardous hourly averages occurred during this time period.

Effect of Air Quality on Hospitalizations

Peak hospital admissions occurred approximately 10 days after the peak in unhealthy $PM_{2.5}$ concentrations (Figure 3). This observation highlights the role of time and the accumulation of unhealthy $PM_{2.5}$ concentrations, which we further explored in the generalized linear model.

Between 1 July and 30 September, 2018, the daily hospital burden of respiratory patients ranged from a low of 3 to a high of 15. The 80th percentile for the 92-day distribution was eight patients. The $PM_{2.5}$ concentration significantly affected the probability of meeting or exceeding the 80th percentile threshold, regardless of duration (X^2 = 16.8 for same day to 23.7 for 11-day average; p = 0.00). The probability of exceeding patient burden increased with both increasing $PM_{2.5}$ and the duration of poor air quality (Table 3, Figure 4). For example, a single-day mean $PM_{2.5}$ concentration of 24 μg m^{-3} (midpoint of yellow or moderate) resulted in a 37% probability of exceeding hospital burden, but the probability jumped to 47 percent if the single-day $PM_{2.5}$ concentration was 201 (midpoint of purple or very unhealthy). Similarly, poor air quality that persisted beyond a single day increased the probability of exceeding burden (Figure 4). For example, a single-day mean $PM_{2.5}$ concentration of 103 μg m^{-3} (midpoint of the red or unhealthy category) resulted in a 41 percent probability of exceeding patient burden (Table 3), but a three-day to five-day mean concentration of 103 μg m^{-3} resulted in 46 percent and 47 percent probabilities of excessive burden, respectively

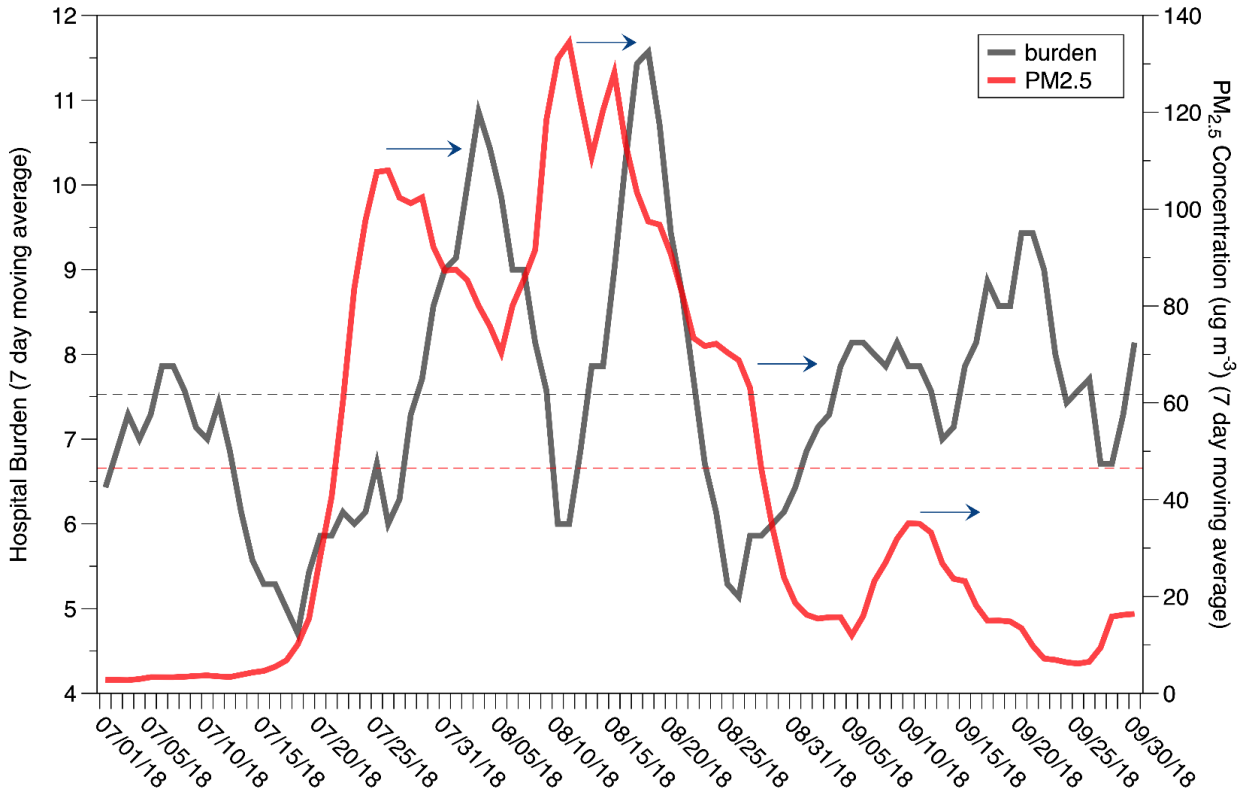

Figure 3. Relation between peaks in $PM_{2.5}$ concentrations (red) and respiratory hospital admissions (gray) from 1 July through 30 September, 2018. The dashed lines represent the mean 7-day moving averages for hospital burden (gray) and $PM_{2.5}$ concentrations (red).

(Table 3). Similarly, if these mean $PM_{2.5}$ concentrations persisted for 7, 9, or 11 days, the probability of excessive burden increased to 49, 52, and 53 percent, respectively (Table 3).

Discussion

The $PM_{2.5}$ concentrations measured during the 2018 wildfire season (Table 2) were similar to those reported during other wildfires. The EPA classifies $PM_{2.5}$ concentrations above 35.5 μg m^{-3} as unhealthy (Orr et al. 2020). Of the six stations in the Rogue Valley, only the stations in Grants Pass and Cave Junction reported a seasonal average below this threshold for the 92-day period that we defined as fire season. The seasonal average at every station exceeded the definition of a smoke wave (>20 μg m^{-3}) during this time (Liu et al. 2017). In wildfires in Victoria, Australia, that burned from late 2006 to 2007, the daily average was much lower (15.8 μg m^{-3}), but the maximum daily average was higher (295.0 μg m^{-3}) (Haikerwal et al. 2016). During the 2007 fires in San Diego County, a much higher daily average (89.1 μg m^{-3}) and daily maximum (803.1 μg m^{-3}) were reported (Hutchinson et al. 2018). The $PM_{2.5}$ concentrations in southern Oregon during 2018 were much lower than those observed during the Seeley Lake fire in Montana in 2017, where average daily $PM_{2.5}$ over 50 days was 220.9 μg m^{-3} and the reported maximum daily concentration was 638 μg m^{-3} (Orr et al. 2020). The Seeley Lake and San Diego fires were closer to their respective smoke-affected communities than the 2018 fires were to the Rogue Valley. The daily average $PM_{2.5}$ concentration in a community 50 miles (80 km) from the Seeley Lake fire during that 50-day period was 47 μg m^{-3}, which is similar to the concentrations over the 92-day period in the Rogue Valley, 20–40 miles (32–64 km) from the

2018 fire season (1 July – 30 September)						
Air Quality Index categories with associated $PM_{2.5}$ concentration midpoints	**Same-day**	**3-day**	**5-day**	**7-day**	**9-day**	**11-day**
Yellow (moderate) 24 μg m^{-3}	37% [27, 48]	34% [24, 46]	33% [23, 46]	33% [22, 46]	32% [21, 46]	33% [22, 47]
Orange (unhealthy for sensitive groups) 45 μg m^{-3}	38% [28, 48]	37% [28, 48]	37% [27, 48]	37% [27, 48]	37% [27, 49]	38% [28, 50]
Red (unhealthy) 103 μg m^{-3}	41% [28, 57]	46% [30, 62]	47% [31, 64]	49% [32, 66]	53% [35, 70]	53% [35, 70]
Purple (very unhealthy) 201 μg m^{-3}	47% [20, 77]	not observed	not observed	not observed	not observed	not observed

Table 3. Probabilities [95% confidence interval], expressed as percentages, of hospitals exceeding the respiratory patient threshold (80th percentile) given mean $PM_{2.5}$ concentrations representing medians of five U.S. Environmental Protection Agency Air Quality Index categories over various durations.

nearest fires. A study in Brazil used nationwide data from 2000–2015 and reported a much lower daily average $PM_{2.5}$ (2.19 μg m^{-3}), but a similar maximum daily average (164.18 μg m^{-3}) (Ye et al. 2021). During the Horse River Fire in 2016, sites in Alberta, Canada reported average daily $PM_{2.5}$ concentrations of 80–293 μg m^{-3}, with hourly maxima of 357–5229 μg m^{-3} (Landis et al. 2018). During the 2011 Richardson Fire in Alberta, Canada, the daily maximum $PM_{2.5}$ was 368 μg m^{-3}, whereas the daily averages were approximately 180 μg m^{-3} (Bytnerowicz et al. 2016).

Our results showed that the average daily $PM_{2.5}$ concentrations for the median moderate (AQI: yellow) were associated with a 37 percent probability of exceeding hospital burden on the same day. However, when air quality deteriorated to median unhealthy (AQI: red), the probability of exceeding hospital burden increased to 41 percent (same-day) and 53 percent (11-day). The maximum average $PM_{2.5}$ concentration for a single day (217 μg m^{-3}) resulted in a 48 percent probability of exceeding burden. At the observed maximum average $PM_{2.5}$ concentration sustained for 11 days (130 μg m^{-3}), the probability of exceeding burden was 60 percent. Additionally, as the mean daily $PM_{2.5}$ concentration increased from median moderate to median unhealthy, the same-day probability of excessive burden only rose 4 percent, whereas the probability of excessive burden rose more than 20 percent when these values persisted for nine days. In the 2006–2007 fire in Victoria, Australia, a same-day increase of $PM_{2.5}$ concentration by 8.6 μg m^{-3} was associated with an increase in emergency department visits for asthma of 1.96 percent; only the same-day association was statistically significant (Haikerwal et al. 2016). In San Diego in 2007, considerable increases in the number of visits for respiratory complaints also were reported, with increases of 3.2 visits per day increase for dyspnea and 1.5 visits per day for asthma in the one to three days after the elevated $PM_{2.5}$ concentrations were observed (Dohrenwend et al. 2013). In Brazil, an observed increase in probability of overall hospital admissions was also reported, but only in the first day of exposure, declining after a 1–3 day lag period. In the latter wildfire, for every 10 μg m^{-3} increase in $PM_{2.5}$ concentration, the probability of same-day hospitalization for respiratory illnesses increased by 5 percent (Ye et al. 2021). No immediate exposure effects were reported during the Seeley Lake, Montana, wildfire in 2017; however, residents exposed to elevated levels of $PM_{2.5}$ during the fire experienced decreased lung function one year after the fire (Orr et al. 2020).

Wildfires and widespread exposure to wildfire smoke pose risks to the infrastructures of hospitals by acting as surge events. Hospital systems invest substantial resources to manage surges in capacity.

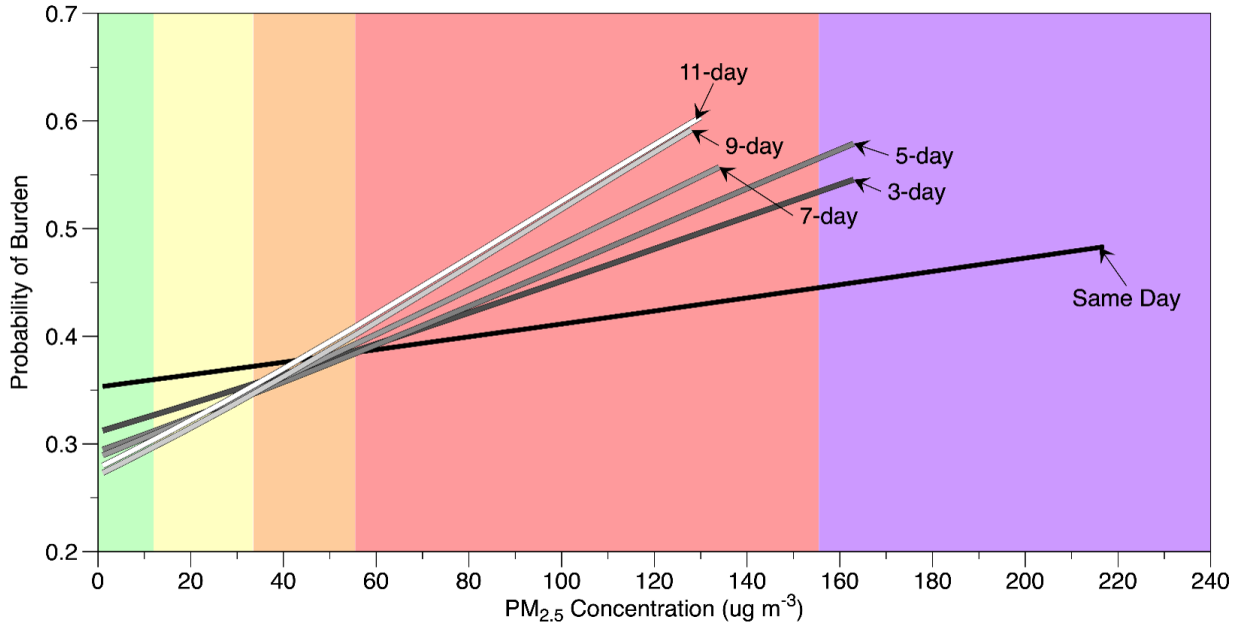

Figure 4. Probability of hospitals exceeding a respiratory patient threshold (80th percentile) given averaged lagged $PM_{2.5}$ concentrations over various durations. Colored regions indicate U.S. Environmental Protection Agency Air Quality Index categories (green = good; yellow = moderate; orange = unhealthy for sensitive groups; red = unhealthy; purple = very unhealthy).

The COVID-19 pandemic has placed a spotlight on the ability of health care systems to manage an influx of patients. However, wildfires and widespread exposure to smoke present a new type of problem. These events typically occur during summer (June–September). Historically, hospitals experienced seasonal burdens of patient flow from illnesses such as influenza, but these typically occur during winter (West et al. 2016). Some studies have indicated that the lowest burden occurs during summer (Walker et al. 2016). Over 25 years ago, Schmidt and Nelson (1996) suggested that a seasonal staffing model should be introduced for nursing units, and that health care organizations reallocate employee hours to match seasonal workload trends of their departments. Our study suggests that climate change, increased prevalence of wildfires, and associated smoke should be factored into the seasonal workload trends of health care organizations in regions that increasingly experience wildfires. We believe that as the occurrence of wildfires increases, health care organizations should consider the impact of a "fire flu" season.

We suggest three future avenues of research on relations between $PM_{2.5}$ exposures and hospital burdens. First, incorporate more years of air quality measures and hospitalization records to determine whether our results are generalizable to years in which smoke prevalence is lower. Additionally, expanding the timeframe may help explain the above-average hospital burden that we observed in months following fire season. Second, investigate the role of productivity in the hospital setting. Hospital productivity refers to the ratio between staff and requirements for patient acuity (intensity of care needed). The ratio of staff to patients depends on the hospital size, number of beds, and intensive care unit capacity. On average, the preferred ratio of intensive care unit beds to respiratory care practitioners is 9:1 (Matthews et al. 2006). Examining the relation between productivity and burden from respiratory conditions during periods of increased volume and acuity of respiratory conditions could further explain hospital burden when smoke is widespread. This type of analysis could also inform changes or procedures implemented by hospitals, such as expanding emergency preparedness plans to include widespread exposure to smoke. Third, evaluate

the transferability of our model in other regions within southern Oregon, such as the Klamath Basin, and expand the purview of hospital burden to other conditions exacerbated by prolonged exposure, such as cardiovascular conditions.

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Tribal Resilience to Climate Change

The effects of and resilience to climate change vary among populations. Marginalized populations, such as Oregon tribes, are more likely to be exposed to climate extremes and associated negative effects on physical and mental health. Accordingly, climate change places disproportionately high stresses on those communities. However, tribal adaptation to environmental and social change over millennia also can enable unusually high resilience. In this section, four early career tribal citizens discuss the ways in which they and their communities are responding to climate change via ceremony, political action, workforce development, environmental stewardship, and youth education and fellowship. The breadth and depth of the events, initiatives, and programs that they describe illustrate the myriad ways in which tribes are exercising self-determination and reclaiming sovereignty despite historic and contemporary inequities.

Salmon Recovery

Kieren Daley-Laursen

Many Northwestern tribes have deep cultural, spiritual, subsistence, and ancestral connections to salmon. The cultural heritage, traditional practices, and modern conservation efforts of tribes reflect the importance of these fishes to tribes that consider themselves to be Salmon People. For thousands of years, oral history has described the relationship of salmon to the people. The salmon gave their hearts and lives so the people could survive. In return, the people now speak for the salmon, who do not have a voice. Salmon was the first being to come forward and give its life to the people as food. Because all of the other animals then were willing to lay their lives down for the people, reciprocity is the law, and people have a responsibility to protect salmon and reciprocate the gift that salmon gave to them. Restoring salmon requires returning fishes to their historical homes, restoring river systems and oceans, and addressing climate change. Protecting and restoring salmon is integral to the cultural survival and economic well-being of Northwestern tribes.

Ceremonies and gatherings are among the ways in which tribes in Oregon and the Northwest honor salmon. Celilo Falls was a traditional salmon harvest and gathering site. Tribes traveled great distances seasonally to fish at Celilo Falls. They constructed villages nearby, creating a vibrant cultural hub (CRITFC 2022). Some tribes hold traditional ceremonies to return the head and tail of the first salmon caught at Celilo Falls back to the river (Woody 2014). These ceremonies honor salmon and contemplate how the lives of salmon support the lives of the community. The installation of The Dalles Dam inundated Celilo Falls in 1957. Tribal elders still remember fishing, feasting, gathering, playing games, and conducting ceremonies at the falls. The loss of this salmon fishery and community place is still felt in communities today (CRITFC 2022).

A recent event to honor the Wykanish [salmon] was attended by many tribes, including the Umatilla, Nez Perce, Jamestown S'klallam, Suquamish, and Yakama Nations (Figure 1). During this event, speakers drew parallels between the struggle of salmon swimming upstream and the efforts of Native Nations to protect salmon in the region. There are many ways in which this metaphor is accurate. For example, treaties in the 1800s between tribes and the U.S. government established trading in the Northwest and gave land rights to the U.S. government. As a result, native ways of life, including traditional salmon harvests, were targeted.

The metaphor also encompasses the dams that have altered traditional ways of life. Many tribes that live upstream from large dams that block fish passage have not been able to harvest from traditional fisheries for nearly a century, and their traditional ways of life have been significantly hindered. Dams have blocked passage to the habitat once available to salmonids and changed riverine conditions in ways that are harmful to salmonids, but dams are not the only cause of salmon population declines. One speaker at the Honor the Salmon event pointed out that salmon are dying of 1,000 wounds that need to be addressed systematically (Confederated Umatilla Journal 2022).

Climate change is one of these wounds. Tribes are acutely aware of the impacts of climate change on salmon, other threatened species, and other cultural resources. Increases in river temperatures directly affect the survival rates of juvenile and adult salmon by increasing the risks of disease, predation, loss of habitat, and death (UCUT et al. 2015). Increases in the frequency and severity of floods damage redds (salmon spawning beds). Extreme droughts reduce flows needed by salmon to migrate. Drought, increases in mean temperature, and heat waves are stressing forest trees and contributing to increases in the frequency, size, and severity of wildfires, causing die-offs and habitat

Figure 1. Salmon laying on a hand-woven tule mat in during a ceremony at the Honor the Salmon event. Photograph by Kieren Daley-Laursen.

loss. According to an assessment of the vulnerability of Pacific salmon and steelhead to climate change, the greatest climate threats to Pacific salmon are ocean acidification, increases in sea surface and stream temperatures, low summer flows, and, depending on the population and life stage, flooding or snowmelt loss (Crozier et al. 2019).

Tribes are experiencing these impacts firsthand. For instance, the McKinney and Yeti fires that occurred in the traditional homelands of the Yurok and Karuk Tribes along the Klamath River were followed by thunderstorms that transported large amounts of sediments to the river. The sedimentation caused decreases in the concentration of dissolved oxygen in the water, resulting in die-offs of salmon, sucker, lamprey, and many other species (Rodriguez 2022). Tribes are taking action to address climate change because its effects on terrestrial animals, fishes, and plants affect tribal cultural heritage and ways of life (ATNI 2022). Gathering and fishing sites and cultural practices specific to tribes are central to a tribe's sense of self, sovereignty, culture, identity, and well-being. The loss of traditional fishing at Celilo Falls is one example of how environmental changes can affect tribes profoundly.

Climate change and other environmental impacts have left many tribes with few or no salmon to harvest. The timing of natural events (phenology) has also been altered by climate change. Traditional knowledge holders are observing changes and experiencing impacts on food harvest due to drought, fire, shifting phenology, and extreme events. Climate change-driven changes in animal migration patterns affect cultural practices such as first salmon ceremonies. Some tribes in Oregon are unable to continue these ceremonies due to a lack of salmon, whereas others have had to alter the traditional timing or structure of these ceremonies to align with salmon runs. All of these factors adversely affect tribes' ability to fish, which in turn decreases the ability of communities to speak their language and sing songs of salmon and ceremonies, eat traditional foods with families and their community, and interact with the environment and sacred places.

Furthermore, declines in salmon populations can be a detriment to the health, economic well-being, and food sovereignty of native communities. A diet that includes fresh salmon decreases the risk of diabetes and heart disease, lowers poverty rates due to increased tribal health and subsistence, and lowers the mortality rates of tribal members (Meyer 1999). Salmon also provide economic benefits to tribal communities, including fishing-related jobs and trading opportunities that afford tribal governments greater economic sovereignty to pursue projects that support their communities. Food

sovereignty allows tribal people to determine their policies related to food and agriculture. The U.S. Food Sovereignty Alliance states, "Food sovereignty goes well beyond ensuring that people have enough food to meet their physical needs. It asserts that people must reclaim their power in the food system by rebuilding the relationships between people and the land, and between food providers and those who eat" (NICOA 2019). Ensuring that tribes throughout the Northwest have access to salmon and salmon fishing sites is an important step in strengthening these relationships among tribes, the land, and first foods.

Speakers at the Honor the Salmon event shared the sentiment that Northwestern tribes are tired of the divide-and-conquer approach to salmon recovery, which largely has been unsuccessful (Confederated Umatilla Journal 2022). Member tribes of the Affiliated Tribes of Northwest Indians (ATNI) have united to formally state their common values, policy goals, and desired outcomes for salmon recovery in the Pacific Northwest. In recognition of the need for collaboration to uphold their sacred cultural commitments to protect salmon (ATNI 2022), ATNI tribes co-produced a unanimous resolution, *We are all Salmon People* (ATNI Resolution 2022-25). Additional tribal organizations such as the Upper Snake River Tribes, Upper Columbia United Tribes, Columbia River Inter-Tribal Fisheries Commission, and Northwest Indian Fisheries Commission participated in the development of the resolution. The resolution aims to create a regional initiative while enabling tribes to pursue their distinct interests and projects related to salmon recovery (ATNI 2022).

The resolution covers themes such as the promotion of cultural welfare and values, sustainable harvest, climatic effects on salmon recovery, integration of best science practices and traditional knowledge, coordination among federal agencies, and adoption of a holistic approach that results in sustainable and resilient habitat for salmon. Parties to the resolution seek to protect and preserve treaty rights, develop partnerships with federal entities, and address the history of failed treaties.

Salmon recovery requires holistic approaches and collaboration among tribes, the federal government, state and local agencies, the public, and many industries in the Northwest, including agriculture, tourism, and energy. Holistic approaches recognize linkages among the land, First Foods, ways of life, physical and spiritual health, food sovereignty, and economic sovereignty. For example, the Coquille Tribe requested that they be recognized as co-managers of Chinook salmon (*Oncorhynchus tshawytscha*) with the Oregon Department of Fish and Wildlife and local governments. This action ideally ensures that the Coquille Tribe has decision-making power while providing further resources to the Oregon Department of Fish and Wildlife. The Cow Creek Band of the Umpqua Tribe of Indians has also requested greater coordination with other states, tribal, and federal governments (Aadland et al. 2022). Many believe such collaborations will benefit all Oregon residents while respecting tribal histories and sovereignty (Aadland et al. 2022).

The holistic approach may seem daunting, but it is feasible. A large wound contributing to the decline of salmon populations is the lack of habitat connectivity. Dams typically reduce habitat connectivity and quality for salmon by increasing water temperatures, reducing dissolved oxygen levels, and disrupting migration and other ecological processes. For decades, the Nez Perce Tribe in central Idaho has called for breaching the four lower Snake River dams to protect Snake River salmonids. In 2020, Idaho Congressman Mike Simpson initiated the Columbia Basin Initiative, which aims to breach the dams to conserve the state's salmon (simpson.house.gov/salmon) (Simpson 2022). Similarly, the Nez Perce Tribe launched the Salmon Orca Project (www.salmonorcaproject.com) to encourage the removal of the dams. In September 2022, NOAA released a report outlining the actions they believe will be necessary to recover salmon and steelhead in

the interior Columbia Basin. Among these actions are reducing direct and indirect mortality from mainstream dams, restoring the Lower Snake River through dam breaching, and restoring salmon passage through areas that currently are blocked (NOAA 2022).

The Nez Perce Tribe is taking proactive steps to mitigate and adapt to climate change and protect fishes by reducing their dependence on fossil fuels and hydropower. Since 2020, as part of an ambitious solar project focused on local energy production and storage, the Tribe has been installing solar arrays on government buildings and their casino, wastewater treatment plant, fish hatchery, and other facilities (Figure 2). In 2021, the Tribe installed the first Tesla PowerPack in Idaho. One goal of the Tribe's plan is to replace the power that the four lower Snake River dams generate (Nez Perce Tribe 2022). The Tribe calls this the 5311 plan because the Bonneville Power Administration reported that 5,311 megawatts are needed to replace the power generated by the four lower Snake River dams at peak capacity (Olson et al. 2022). Recognizing that they need not tackle this project alone, the Nez Perce Tribe created the Nimiipuu Energy Cooperative (www.nimiipuu.energy), which allows tribes to create, distribute, and share energy through a virtual power plant system. A virtual power plant is a network of power generators, such as solar panels or wind turbines, that are connected to users and energy storage through a centralized control system. A virtual power plant differs from traditional power plants by enabling independent ownership and maintenance of storage and generators while sharing or distributing energy as needed (Deign 2020). The Tribe recognizes that their early adoption in this area positions them as a resource to other tribes in the region that are interested in joining the cooperative and replacing energy produced by dams. The Nez Perce Tribe plans to produce 10 percent of the power needed, or 531 megawatts on the reservation, and to recruit other tribes. As other tribes join the cooperative, the collective potential to reach the 5,311-megawatt target increases (Nez Perce Tribe 2022).

Figure 2. Solar installation on Tribal lands. Courtesy of the Nez Perce Tribe.

Along with recovery projects led by organizations such as CRITFC and UCUT, the Nimiiupuu Energy Cooperative exemplifies the holistic approach called for by ATNI's *We are all Salmon People* resolution. As the rights of tribes in the Northwest to gather, hunt, and fish are deteriorating, collaboration becomes even more central to recovering the salmon that are the lifeblood of many ecosystems; recognizing, honoring, and incorporating tribal culture and values as integral to that recovery; and supporting historical, economic, and cultural practices of native cultures in perpetuity.

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Internships and Youth Programs Grow Climate Science Interest and Tribal Capacity

Lyndsi Lewis

My first job, at the age of 14, was facilitated by a summer youth program provided by my Tribe, the Confederated Tribes of the Umatilla Indian Reservation (CTUIR). As an employee in the Tribal Housing Department, I learned to answer telephones in a professional manner and assign tasks to employees in the shop. My summer job provided a foundation that would shape my work ethic and understanding of the employment services my Tribe offers to our people.

This past summer, my youngest son, who is in his junior year of high school, participated in the same summer youth program. Because climate change is high on his personal list of educational priorities, we requested that he be placed in the Department of Natural Resources. This request was met, and my son was employed by the Tribal Energy and Environmental Science Program, where he learned about the projects that CTUIR is evaluating to combat climate change and preserve our First Foods. It was inspiring to see how much the summer program has grown since I participated in it. In addition to the work experience, my son's cohort visited a nearby college campus to discuss higher education and a newly introduced scholarship program that is designated to benefit CTUIR members. They also learned about a program the college offers in which students spend three years learning biology or geology for a bachelor's degree and then transfer to an Ivy League school for a graduate program in forestry. This opportunity has sparked my teenager's determination and trajectory.

Figure 1. Frank Lake, Joe Hostler, Coral Avery, Brandon Tweig, and Margo Robbins (left to right) descend from a meadow to an oak woodland as they discuss the application of traditional knowledges and approaches to cultural burning to manage forests for culturally important uses. Photograph by Chas Jones.

Tribal governments have a unique opportunity to provide educational environments for tribal students. Not only the CTUIR but many other tribes have created youth programs that place students within departments of their interest, enabling them to gain experience and earn a wage during their summer breaks. The summer programs introduce tribal students to some of the basic policies of the tribal government and allow them to explore their professional interests. The programs also create relationships between students and mentors. Whether children are raised on a reservation or in an urban setting, tribal youth internships foster intergenerational cultural and spiritual connections to the landscape. Internships such as my son's allow for immersion

in traditional stories and management practices in a respectful and professional environment, encouraging tribal youth to continue the practice of their culture, which is founded in natural resources (Figure 1).

I am so pleased that my 16-year-old son had the opportunity to participate in CTUIR's summer internship program. He was introduced to pre-college and pre-employment perspectives while sparking his interest in science, technology, engineering, and mathematics. I have witnessed the inspiration that he gained by visiting a college campus and discussing his next steps after graduating from high school, and his newfound discipline and engagement in his current studies. His engagement with hands-on learning gave him an example of what his career could look like if he continues on the educational path he is currently pursuing. Inspiring youth at the earliest age stimulates their curiosity in climate and science and will help tribal communities adapt and become more resilient to climate change.

When I started community college, pursuing an associate degree in civil engineering, I became an intern with CTUIR's Department of Science and Engineering. The internship provided my first opportunity to observe my Tribe's work with the U.S. Department of Energy on environmental and climate issues, and I became passionate about making the environment sustainable for seven generations to come.

As a means of training individuals early in their careers to meet environmental and climate challenges, interns are provided with both education and real-world work experiences. Tribal internships engage and recruit potential employees while providing cultural understanding and perspective. Incorporating traditional values of CTUIR into the internship program connects potential employees to the foundation of the Tribal government and will ultimately support the Tribe in retaining employees and expanding its capacity.

After my recent graduation from Oregon State University, I wasn't sure if attending graduate school was what I wanted. I also wasn't sure if entering the workforce immediately would enable me to have the impact I hoped. As an intermediate step, I accepted a fellowship with the Affiliated Tribes of Northwest Indians. For ten months I am working with non-profit organizations, tribes, and state and federal entities and programs. This fellowship has given me time, experience, and the opportunity to seek mentorship. With time, I am weighing my options for continuing my education with a view of what is needed in the field and how climate change is being addressed on different levels. The experience I am gaining will help me make the best decision. The most important opportunity, in my opinion, is building a mentor-mentee relationship: connecting with individuals I admire and respect to gain personal insight into what will be a fulfilling and impactful career.

Land Stewardship, Food Sovereignty, and Mitigation of Climate Change Impacts

Kylie Avery

I was invited to join the Swinomish Tribe in building a piece of history on a day with one of the lowest tides of the year. After six years of waiting for permit approval, the Swinomish Indian Tribal Community was allowed by the U.S. Army Corps of Engineers to construct a clam garden on the shores of Kiket Island in Puget Sound, most of which is designated as Kukutali Preserve (Figure 1) and managed by the Washington State Parks and Recreation Commision and the Swinomish Tribe. Throughout the day, our introductions, conversations, and prayer were interrupted by loud military jets that flew overhead to nearby naval air stations. It served as a reminder of how a branch of the U.S. Department of Defense had jurisdiction over the tidal wetland and the power to give or deny the Swinomish permission to engage in land stewardship and tradition that has been practiced by the peoples of this region for millenia. But the day stood out as a great milestone for self-determination and tribal sovereignty, and for the Tribe's ability to mitigate the effects of climate change on coastal ecosystems.

Figure 1. Kukutali Preserve. Photograph by Kylie Avery.

Larry Campbell, a Swinomish elder, started the introductions by recognizing the western scientists who were present at the Tribe's invitation. He spoke about the importance of blending traditional knowledges and western science to alleviate the effects of climate change, and recognized that we had become a community. We now shared relations and family as we came together to give back to the First Foods, the land, and the Tribal community. A Swinomish council member told us that as Coast Salish peoples, their hearts were on the beach, and shared a common Coast Salish saying: "When the tide is out, the table is set." This proverb speaks to the significance of being able to practice one's culture and connect with a First Food that feeds both body and spirit. Alana Quintasket, a member of the Swinomish Tribal Senate, shared the story of a 4000-year-old clam garden that was abandoned when colonization began. Without the Indigenous people to turn over the clams through harvest and management, the garden died.

Clam gardens, which are constructed in intertidal zones, maximize productivity of these shellfish by building up the beach and providing a level surface on which the molluscs can grow. As described by the Swinomish Climate Change Initiative (2022), retaining layers of shells from clams and other species contributes to adaptation as the ocean becomes more acidic. When atmospheric concentrations of carbon dioxide increase, carbon dioxide enters the ocean and alters its chemistry,

reducing its pH and inhibiting shell formation in many species. The decomposition of shells from previous generations of clams in the gardens increases the local pH of the seawater. Clam gardens also increase local species richness by creating habitat for other native species, such as kelps and sea cucumbers (Swinomish Climate Change Initiative 2022).

Figure 2. The previous day's work on the clam garden wall was visible at low tide. Photograph by Kylie Avery.

When we arrived at the beach, the tide had dropped to its lowest level, allowing us to see the work completed the previous day by the Swinomish community (Figure 2). A substantial number of the people who contributed to building the garden were youth. We began to pick up the rocks that lay 25 meters from the edge of the clam garden wall. At first, we each picked up heavy rocks with our gloved hands and moved them toward the water, but we soon formed a human chain to pass rocks down the shore (Figure 3).

Figure 3. A view toward the clam garden from the picnic area. The chain of people passing rocks is on the left, and those gathering larger rocks with equipment are on the right. Photograph by Coral Avery.

As we carefully received and passed the rocks, we shared stories and backgrounds. I met people with whom I wouldn't otherwise have been able to connect: community members from the Malahat First Nation and Pauquachin First Nation who traveled from Canada to offer assistance, and invited researchers and reporters who captured the significance of the day. Others who weren't part of the chain moved the largest rocks with hand trucks and sturdy wagons. At the waterline, Swinomish community members shuffled the rocks to fill gaps in the walls. By the time the tide started to rise above the clam garden wall, our group had collectively moved about 20 tons of rock. We were part of something that will outlive us and hopefully will be present with the Swinomish people for the next millennium (Figure 4).

As I traveled home, tired and starting to feel sore, I reflected on everything that we had accomplished. My heart is still full from the

family of which I was a part. One of our group members said that everyone who needed to be there that day was there; that all of those who were there to share stories, lay their hearts on the beach, and stand witness and contribute to a great accomplishment were present. We built a wall not to separate people, but to connect them and to stand as strong as the hands and hearts that built the wall. I cannot express how honored and grateful I am to have been a part of reclaiming traditional knowledge, land stewardship, and culture in the face of colonization and climate change.

Figure 4. The clam garden wall at the end of the day, when the tide began to rise. Photograph by Kylie Avery.

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Including the Next Generations in the Climate Change Conversation

Kylie Avery and Zoe Roberts

In August 2022, the Upper Snake River Tribe (USRT) Foundation held their first Tribal Youth Climate Camp. Nineteen students from 12 to 17 years of age from three of the member tribes (Shoshone-Bannock, Shoshone-Paiute, and Fort McDermitt Paiute Shoshone) and who live on one of the member tribes' reservations came together for three days in Boise, Idaho, to learn about climate change. Accompanying the students were Zoe Roberts, Environmental Specialist with USRT and the camp's organizer; Kylie Avery, Affiliated Tribes of Northwest Indians Climate Intern and camp chaperone; and additional chaperones from the USRT member tribes. The camp was held in the Treasure Valley and along the Boise River (Figure 1). Prior to colonization, these were vital gathering areas for the nomadic tribes throughout the region. In late spring and early summer, tribes gathered along the Boise River to fish for salmon, perform ceremonies, and commune with one another.

Figure 1. The view from Bogus Basin Mountain Recreational Area. Photograph by Kylie Avery.

The main focus of the youth climate camp was water. Activities included rafting the Boise River, visiting the Boise WaterShed Environmental Education Center to learn about the urban water cycle and discuss water conservation, hiking in riparian and sagebrush shrubsteppe ecosystems and talking about their relations to water, and hiking around the Boise River Dam. Water and climate are key concerns for many of USRT's member tribes. Not only do hydroelectric dams, declining fish populations, temperature changes in and out of the water, and water legislation affect tribal life, but they may be confusing to children and teenagers. USRT hoped that by drawing connections between climate change and water, the students could begin to connect the practices and concerns of their tribes with the changing climate.

The camp occurred during a heat wave, and the Boise River was the best place to cool down. Observations while rafting illustrated the importance of the river for the surrounding plants and animals, and as a source of recreation. Many of the students had not previously visited or entered the Boise River, and both they and camp leaders were humbled and rewarded by the experience. The river is fed by snowmelt, and its water, like that of many other rivers in the Northwest, is preserved as a resource for people late into summer by a series of dams. One of the impacts of climate change in the region is a reduction in the percentage of precipitation falling as snow during the colder months, which contributes to an increase in the length and severity of drought.

Figure 2. Students wade through the Boise River to catch macroinvertebrates. Photograph by Kylie Avery.

At the Boise WaterShed, a learning center that hosts educational programs at the West Boise Water Renewal Facility, the group was shown that one of the ways in which Boise is conserving water is by thoroughly cleaning wastewater and releasing it back into the Boise River. The students enjoyed testing the quality of the recycled water by searching for macroinvertebrates that are sensitive to pollution (Figure 2). They placed tools such as kick nets and D-ring nets downstream to catch insects, snails, and worms that were displaced from rocks and sediment as the students waded through the river. Taxonomic orders and life stages such as mayflies and stonefly nymphs cannot tolerate poor water quality, and therefore their presence suggests that water quality is high (Figure 3). Additionally, the students were uplifted by talking about the effects of drought while being exposed to part of the solution.

After collecting macroinvertebrates, the students participated in a discussion of water management practices, water rights, and climate change. The students were asked to read quotations from historical water managers and select the quotation that resonated with them most strongly. Many students selected quotations stating that water shouldn't be over-consumed by private companies. Others selected quotations about water's service as a resource for every living thing or that noted that no one state, country, or private entity should have full control over water use. The educators posed the question, "In a perfect world, what would water management look like to you?" Many students said that water would be available to all and wouldn't be polluted by waste. The goals of this exercise were for the students to think critically about contemporary water management and to be empowered by visualizing their role in changing water management.

Figure 3. Students separate and identify macroinvertebrates caught in the Boise River. Photograph by Kylie Avery.

After visiting the Boise WaterShed, the group hiked in sagebrush shrubsteppe, which occurs throughout the Intermountain West (Figure

4). Many traditional foods and sacred medicines, including sagebrush (*Artemisia* spp.), grow in this ecosystem. The sagebrush shrubsteppe is threatened by drought and by non-native invasive species such as cheatgrass (*Bromus tectorum*), which in turn threatens food cultivation and harvest of medicine. Some of the discussions during the hike, echoing those about water conservation, emphasized the scarcity of resources. One of the chaperones spoke about food shortages in her community and the greenhouses the community is constructing to help supplement its food stores. Another chaperone explained that the reservation on which she lives is in a food desert, where grocery stores are scarce, expensive, and have few healthy options such as fresh produce. The effects of climate change directly affect food sovereignty and therefore the culture and health of Indigenous communities.

Figure 4. Youth hike through sagebrush shrubsteppe outside of Boise, Idaho. Cheatgrass, a highly flammable, non-native invasive species, is especially prevalent in this area. Photograph by Kylie Avery.

Figure 5. The Boise River Diversion Dam. Workers on the bridge are lowering boards to decrease the river's flow. Photograph by Kylie Avery.

Next, the students visited the Intermountain Bird Observatory, where scholars from Boise State University joined them to talk about the Boise River Diversion Dam (Figure 5) and some of the bird species that migrate through the region. The group saw that wooden boards are being added to the dam to reduce the flow of the river and increase water retention, and learned that similar boards have been used since the dam's construction in 1906. As one of the camp's chaperones explained, their Shoshone ancestors used a similar process to control the river flow for hundreds of years prior. They were stewards of the local land until they were displaced by colonization. Being reminded of that heritage by someone from the group was significant in changing the narrative to better reflect the history of land stewardship in the region.

Among the primary goals of the camp were to encourage students to be curious, ask questions, and draw connections among seemingly unrelated issues. The camp brought together students from three different reservations and allowed them

to talk about their experiences. Friendships grew between strangers within minutes. The students realized that their experiences may be similar, which can help them feel less overwhelmed or alone. A deep connection with another tribal student whose community is facing similar challenges due to climate change may be positive and last for years to come.

By the second day, many students felt comfortable enough to share their own experiences with climate change and other global events. One student explained that during the toilet paper shortage at the beginning of the COVID-19 pandemic, her community shared their supplies instead of hoarding. She anticipates that her community again will share if water or food shortages occur in the future. Many of the students had similar stories of members of their communities helping each other during hard times. Most of the students had sophisticated ideas about community and responding to climate threats. Some just needed a safe place where they could voice their thoughts, fears, and ideas. Sending students home with a head full of knowledge about climate is good, but sending students home with a head full of questions and ideas is far better.

The message surrounding climate change is urgent. But being able to start learning about climate change in a fun and lighthearted way is beneficial, especially for youth. Climate change is a heavy topic that can easily influence one's mental health. Occasionally reminding oneself of the progress being made is crucial. It's grounding to be surrounded by teens that just want to play in the river or enjoy scenic views with their friends. These students are the future of their communities and culture. If even one student returned home after the trip and asked their elders what they can do to protect against and adapt to the effects of climate change, the camp has enabled a leap toward progress.

Social Systems

According to the Yale Program on Climate Change Communication, which rigorously tracks public opinion and behavior related to climate change, about 74 percent of Oregonians recognize that global climate is changing (climatecommunication.yale.edu/visualizations-data/ycom-us). Sixty-six percent of Oregonians are worried about the effects of these changes, whether their focus is personal harm or harms to disadvantaged populations, future generations, or plants and animals. In this section, we focus on two ways in which residents of Oregon and other states and regions are responding to climate change: with visual art and with food systems. Visual artists are using their talents to bear witness to the ways in which human and natural systems are being affected by climate change. In the process, they are informing viewers, engaging their audience in conversation, and sparking cultural change. Meanwhile, those who raise food professionally or for themselves and their families are exploring how soils can be managed sustainably and, where necessary, restored. Scientific evidence suggests that the feasibility of the set of practices commonly referenced as *regenerative agriculture,* and the effects of those practices, vary among locations and as climate and other environmental conditions fluctuate. Charitable and potential federal investments in regenerative agriculture will provide greater clarity on the potential magnitude of benefits to food security, nutrition, livelihoods, and the natural environment.

Art and Climate Change

Dominique Bachelet

Visual artists have illustrated weather events, seasonality, and local climatic conditions through the ages. By doing so, they created a valuable record that provides information about past extreme events that affected societies and about climate variability. Many artists today have either witnessed or been affected personally by weather events that have been linked to ongoing climate change. Their reflections can be classified into three types of engagement: in art, where the medium is used to inform viewers about climate change; with art, where the medium engages the audience in conversation and information sharing; and through art, which can lead to cultural evolution and transformation (Bentz 2020).

Figure 1. *Climate Change* by Bart Walter on exhibit in Asheville, North Carolina, February 2020. Photograph by Dominique Bachelet.

In art, the most common use of art, bears witness to climate extremes and trends during the artist's lifetime. For example, Bart Walter's *Climate Change*, a sculpture of a polar bear, was included in the travelling exhibition *Environmental Impact II* (Figure 1). Roosen et al. (2017) commented, "Perceiving art demands attention, and processing art requires parts of the brain that are not normally accessed by typical communications about climate change." Bryan David Griffith's *Two Degrees of Impact* (Figure 2), part of his solo exhibition, *Rethinking Fire*, at the World Forestry Center in Portland, Oregon, referenced the research of Matthew Hurteau. This research suggested that protecting the large trees that can capture and store considerable amounts of carbon can help limit mean global temperature increases to less than 2°C (3.6°F) above pre-industrial levels.

Figure 2. David Griffith's *Two Degrees of Impact* on exhibit in Portland, Oregon, September 2022. Photograph by Dominique Bachelet.

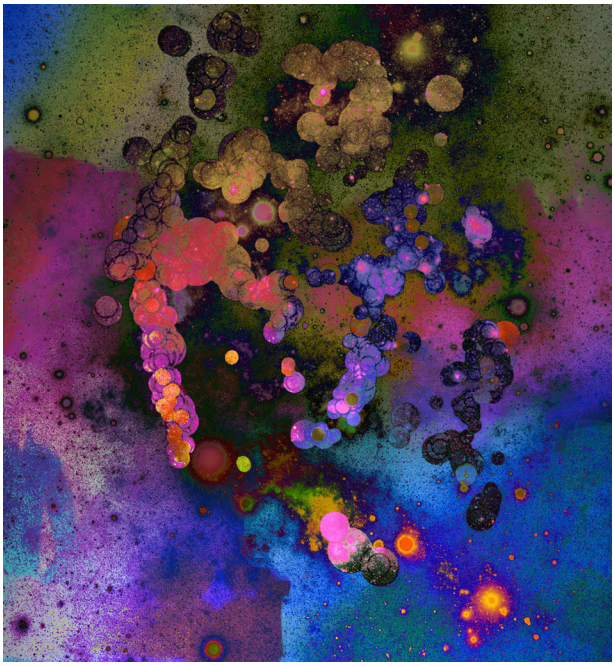
Art is an effective means of science communication (Roosen et al. 2018) because it provides visual aids to introduce an issue and demonstrates the artist's personal reaction to events or the effects of events. As a result, events and their effects do not become abstractions that occur elsewhere or during other periods in time.

Daniela Noemi Molnar describes her work as a way to confront grief. Her series *New Earth* (www.danielamolnar.com/project/new-earth/new-earth-26/?cat=artwork#1) depicts the new shapes that glacier melt has revealed (Figure 3). Inspired by satellite imagery, she paints the reshaping of Earth by climate change.

Figure 3. *New Earth 26 (Alaska)* by Daniela Molnar.

Figure 4. Sabra Comins's *Fingers Crossed She Will Fly Unbound* on exhibit in Corvallis, Oregon, October 2021. Photograph by Dominique Bachelet.

Scientists' stories have inspired artists such as Sabra Comins. In her art that was included in the exhibition *What Will Nature Do?* at the Arts Center in Corvallis, Oregon, in autumn 2021 (Figure 4), Comins wanted to illustrate that although some species will likely become extinct as climate changes because their physiological thresholds will be exceeded, other species will escape those constraints and survive. She believe there is hope in the message from scientists that adaptation often is possible: "In [a scientific presentation], I heard nature is tough and people need to get out of the way . . . These butterflies are about to fly free of any constraints of our knowledge."



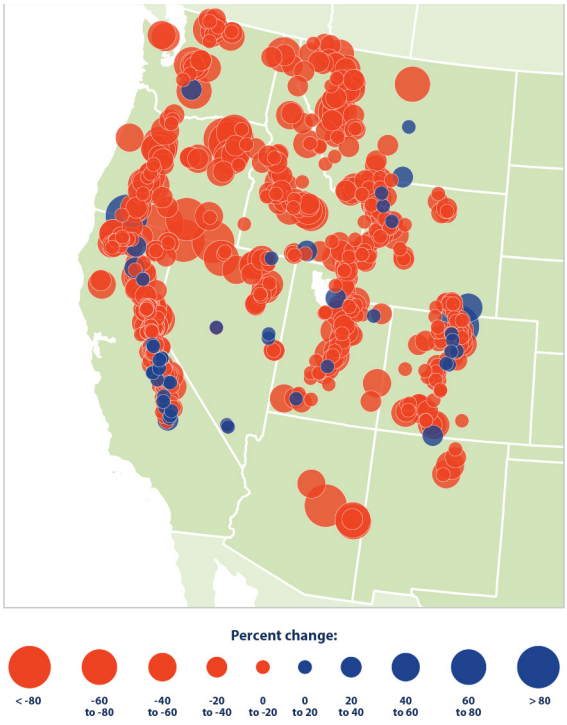


Figure 5. (Above) *Snowpack Trends in the Western US* by Alisa Singer. (Right) The data that inspired Singer's art (EPA 2016).

Alisa Singer painted an image that reflects a figure in the U.S. Environmental Protection Agency's guidance on snowpack as an indicator of climate change (EPA 2016). The image was derived from published data on changes in snowpack in the western United States (Mote and Sharp 2016) (Figure 5). Singer's series *Environmental Graphiti: The Art of Climate Change* (www.environmentalgraphiti.org) includes over 100 digital paintings, each of which is derived from a graph, map, word, or number relating to key facts or data about climate change. Her art has been featured on the covers of three recent reports of the Intergovernmental Panel on Climate Change (IPCC). The cover of the 2018

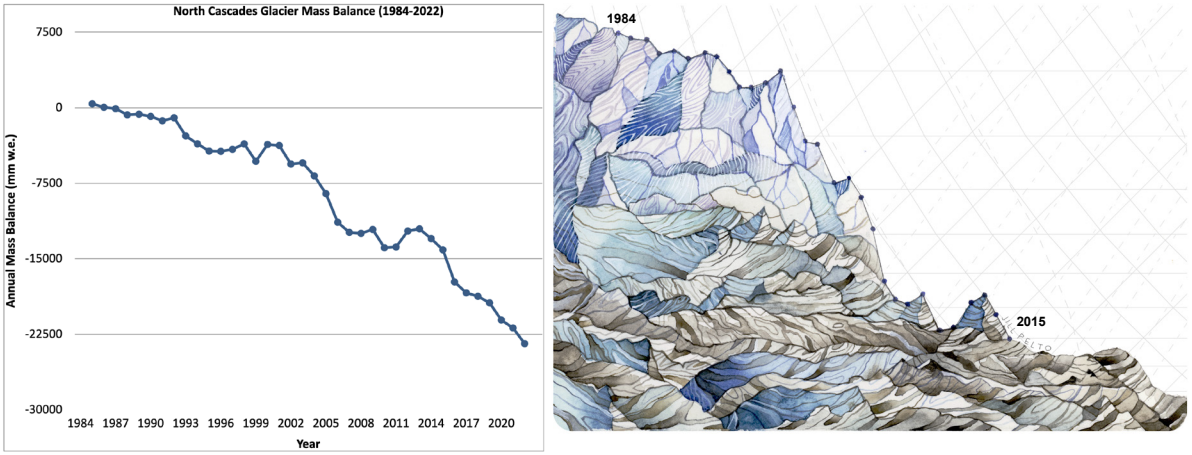


Figure 6. *Glacier Melt* by Jill Pelto.

report (Masson-Delmotte et al. 2018) was the first to feature art, a reflection of the scientific community's growing embrace of art as a powerful means of communicating the effects of climate change. Singer believes that "art makes the science more accessible and science makes the art more meaningful." Some artists who are also scientists, such as Jill Pelto, are using their scientific data as inspiration for an artistic expression of climate change (Figure 6).

Engagement **with art** aims to create opportunities for discussion that can bridge and integrate opposing interests and different forms of knowledge. Art and science projects can help develop a dialogue between artists and scientists and create a new, potentially more effective means of communicating scientific results to a general audience.

Because images can convey so much information, art can enable diverse viewers to understand the many facets of climate change (Bentz 2020). David Moyers's *Climate Change* (davidmoyers.com; Figure 7) demonstrates how flooding and wildfires are linked to emissions from trucks and cars and to elements

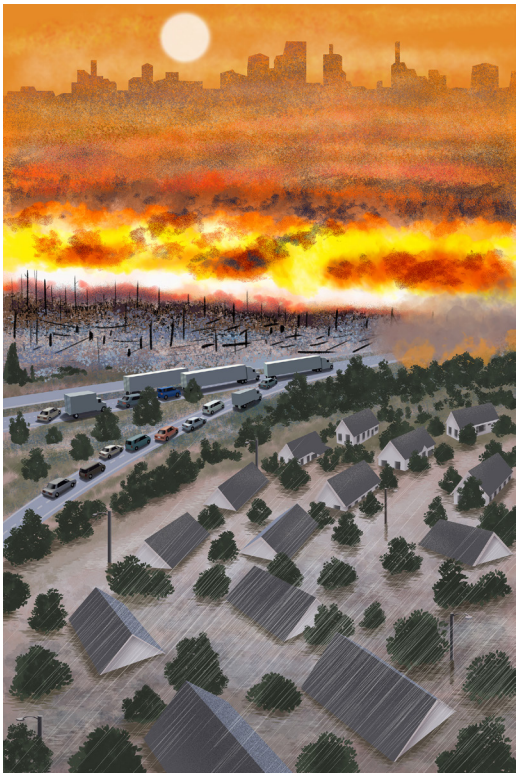


Figure 7. *Climate Change* by David Moyers.

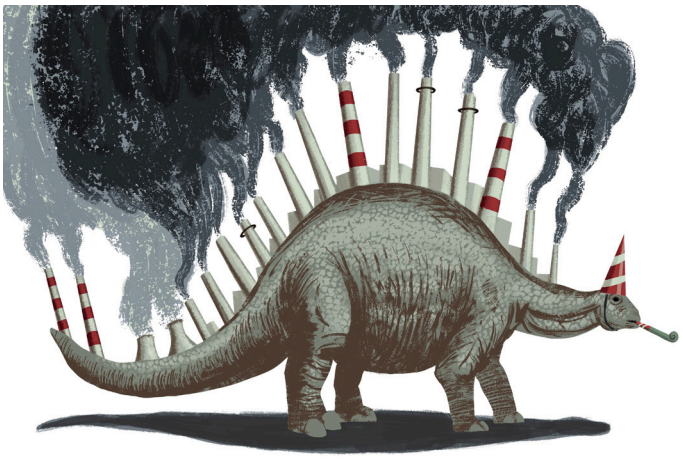


Figure 8. *Fossil Fuel Industry* by David Moyers.

of suburban lifestyles, such as daily commutes by motor vehicles. His art highlights the role of the oil industry in generating emissions of greenhouse gases (Figure 8).

Engagement **through art** intends to connect with its audience and ultimately motivate members of the audience to act differently. In this context, the role of art is to drive societal transformation in a changing climate. As the writer Zoë Lescaze (2022) commented, "The most effective protest art . . . does not confront us with evidence we've already proven perfectly willing to ignore. Instead, it broadens the narrow ways in which we tend to conceive of time and our position within larger ecologies, without necessarily mentioning climate change by name. The resulting works are not demands for immediate action but ones that expand our psychological capacity to act." Hannah Rothstein (www.hrothstein.com/#/national-parks-2050) calls her pieces a "call for action." She attempts to make the impacts of climate change feel more tangible by choosing places beloved by the American public and illustrating how those places will change unless decisions are made to

Figure 9. *National Parks 2050: Redwoods* by Hannah Rothstein.

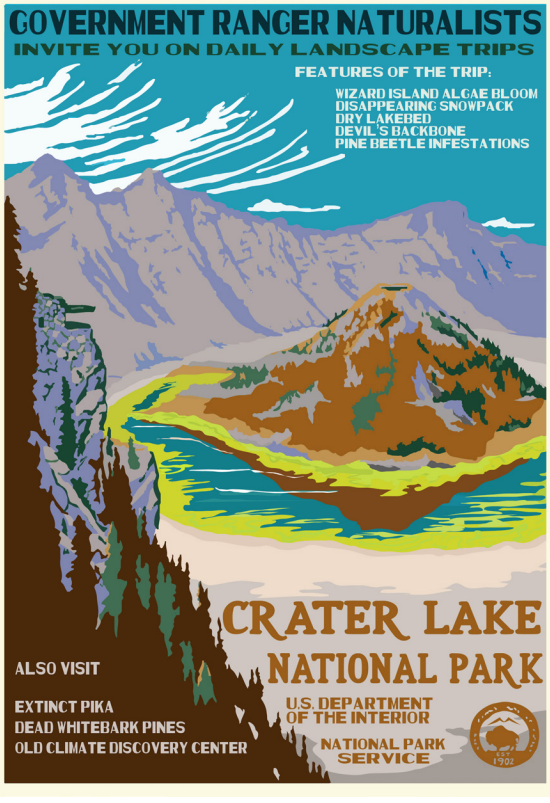


Figure 10. *National Parks 2050: Crater Lake* by Hannah Rothstein.

reduce emissions (Figures 9, 10). Art's power to evoke emotions can sensitize the public to climate change and its likely effects on Earth, including human societies.

Figure 11. *Not Yours, Not Mine, Is Ours* by Daniela Arenas. Photograph by Heather Moran / College of Charleston.

The desire for action is shared by numerous young people, who have created emotionally evocative paintings such as those included in the 2020 Student Art Expression of the Year program. Daniela Arenas, a student at the College of Charleston (South Carolina) who received one of three program's three awards, said, "I believe art speaks to people and it can influence how people feel and act. The message behind [my painting] *Not Yours, Not Mine, Is Ours*, is to show everyone the reality of what human-caused global warming is doing to our world and hopefully, make us take action . . . When viewers see this painting, my hope is that it prompts them to understand that it's in our own hands to change the world" (Figure 11). Similarly, Fiona Sieber, a high school student who painted an astronaut holding Earth between their hands, explained, "With my art I hope to show that the human race has the future of the earth in our hands." Sieber's painting was included in a virtual, community art space exhibition by students of Robert Bateman Secondary School's Art Activism class. The exhibition was presented in partnership with The Reach Gallery Museum in Abbotsford, British Columbia, in 2020.

Tom Christophersen, head of the Nature for Climate branch of the United Nations Environmental Programme, commented, "The main challenge is the lack of human imagination; our inability to see a different future because we're staring down this dystopian path of pandemic, climate change, biodiversity loss." Art may inspire younger generations to develop new policies and change attitudes and behaviors in ways that will eventually reduce global emissions of greenhouse gases.

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Regenerative Agriculture

Dominique Bachelet

Soil degradation generally is characterized by loss of organic matter, declining soil fertility and structural complexity, erosion, adverse changes in salinity or pH, or high levels of toxicants. Soils are degrading worldwide (Rekacewicz 2007), and over 40 percent of agricultural land is seriously degraded due to intensive human activities (Jie et al. 2022). The Dust Bowl in the United States during the 1930s exemplified how the interaction of drought and agricultural practices may cause extensive soil losses. In the United States, the volume of soil organic matter is currently about 50 percent of that present when forests and prairies were converted to agricultural land, primarily during the 1700s or 1800s (Baumhardt et al. 2015). Since World War II, farmers have used tillage and synthetic fertilizers to boost production. Tillage—aeration or turning of the soil, often by mechanical means, in advance of planting—increases emissions from decomposition and increases soil erodibility. Each year, 0.3 percent of global food-production capacity is lost to soil erosion and degradation (FAO and ITPS 2015). Regeneration of 25 mm (1 in) of topsoil requires approximately 500 years, and agricultural production generally requires a topsoil depth of 150 mm (5.9 in) (Pimentel 1998).

The ultimate goal of regenerative agriculture is to restore degraded soils and manage them sustainably (Lal 2020) (Figure 1). There is no consensus definition of regenerative agriculture (Newton et al. 2020) despite use of the term since the 1980s (Giller et al. 2021, O'Donoghue et al. 2022). Nevertheless, three principles generally characterize regenerative agriculture. First, minimize physical and chemical disturbance of the soil. Second, cover the soil to reduce erosion. Third, diversify crop rotations to manage pests and pathogens and provide diverse nutrients to the microbial community in the soil. Benefits of these practices include comparable yields from regenerative and conventional operations (Jordon et al. 2022) and minimal erosion as a result of extreme weather. As soil carbon content and water retention increase, so does the potential for higher farm revenues through reduced use of fertilizers, herbicides and pesticides, and fossil fuel-powered machinery. Furthermore, reduction of fertilizer applications tends to improve water quality by reducing runoff of nitrates into surface water or infiltration of nitrates into groundwater. Because synthetic and organic fertilizers increase the amount of nitrogen available to soil microbes, which turn nitrogen into nitrous oxide, a potent greenhouse gas, decreases in fertilizer use also mitigate emissions. The focus on soil aims to maximize long-term yields while minimizing application of chemicals (Lal 2020). By contrast, conventional agriculture often maximizes short-term yields with addition of synthetic fertilizers and pesticides.

The feasibility of adopting regenerative practices varies among locations. Conversion from conventional to regenerative agriculture also can incur substantial up-front equipment and labor costs. Because regenerative practices are based on maximizing soil condition and native species richness in agricultural lands, they have much in common with practices promoted for sustainable agriculture, climate-smart agriculture, organic farming, and agroecology. Which practices are applied will vary on the basis of soil conditions. The most common and accepted practices are no till, cover cropping, integrated nutrient and pest management, complex rotations, and integration of crops with trees and livestock.

No till, or minimum tillage with residue mulching, enhances the formation of soil aggregates, enriches organic matter in the soil, sequesters carbon, increases water infiltration into groundwater,

and increases soil water content. However, some soils develop hardpans that, left intact, can constrain root zones and thus reduce yields.

Cover cropping protects the soil surface with plants with the goal of reducing soil erosion; improving water retention; managing weeds, pests, and diseases; and increasing the species richness of soil microbes and insects that serve as pollinators. In Oregon, common cover crops include winter oats, cereal rye, crimson clover, Austrian field peas, and common vetch. Cover crops may be used for forage or, especially when they are legumes, as mulch to return nutrients to the soil. Use of cover crops generally increases soil organic matter and carbon sequestration. The benefits from cover cropping over time depend on initial soil conditions, type of cover crop, weather conditions, and timing of cover cropping.

Integrated nutrient and pest management minimizes chemical use and maximizes the efficiency of chemicals when they are used. Regular monitoring and knowledge are required to recognize signs of pest outbreaks. A diverse soil microbiota contributes to availability of nutrients and carbon to both plants and microbes. In the United States and Europe, it usually is feasible to reduce fertilizer use. However, use of fertilizers often is necessary to increase nutrient levels in eroded African soils.

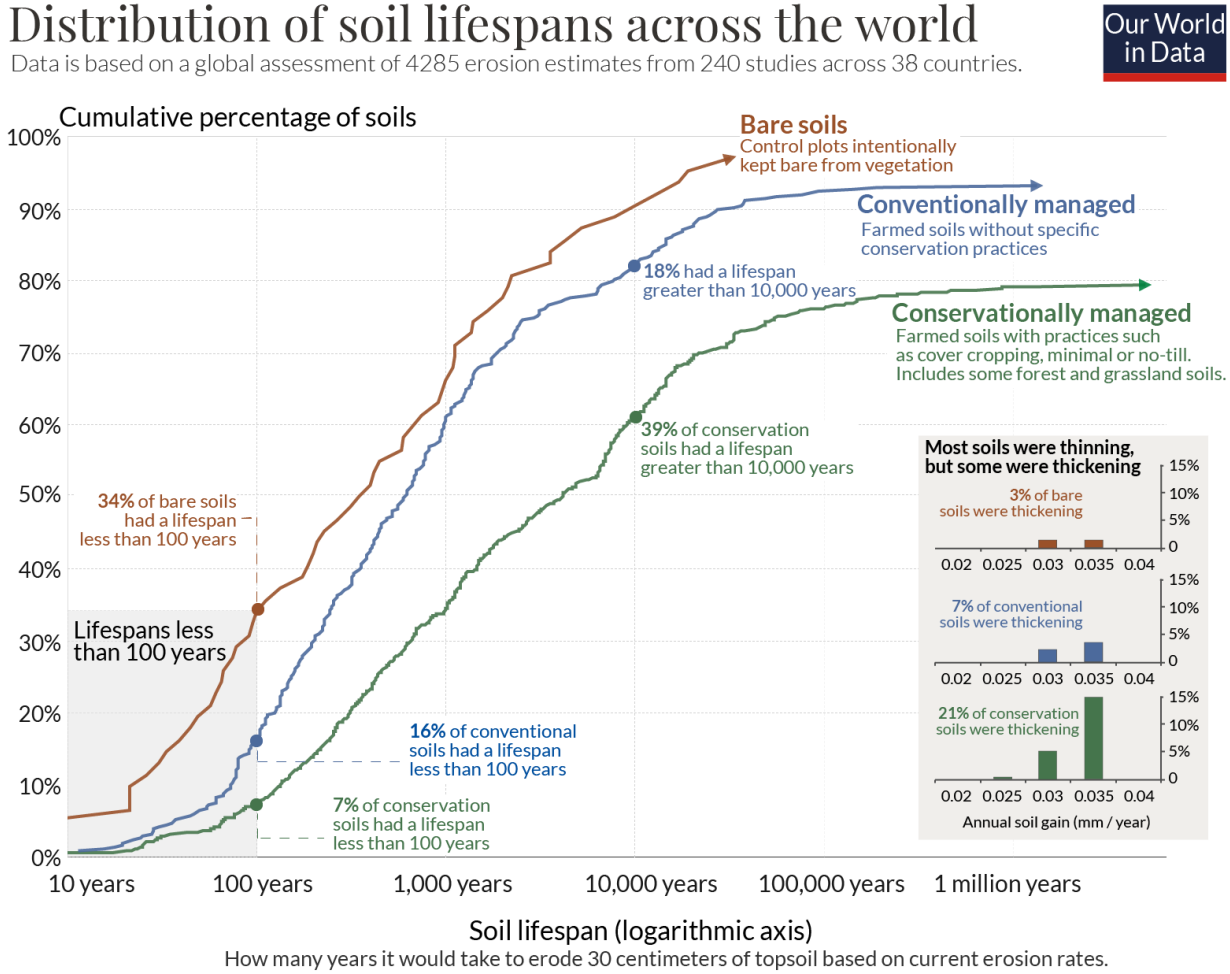

Figure 1. Distribution of soil lifespans worldwide. Source: ourworldindata.org/soil-lifespans.

Complex rotations can improve soil fertility by alternating a nitrogen-fixing with a nitrogen-hungry crop and increase native species richness by alternating crops that attract different types of insects that serve as pollinators. When complex rotations include cruciferous plants such as rapeseed or mustards, which contain glucosinolates and suppressing weed growth for weeks to months after mulching, the need for herbicides also is reduced.

Integration of crops with trees and livestock can reduce the volume of fertilizer and animal feed used and labor and machinery costs, thereby increasing farm revenues. Incorporation of fresh manure into soil by hooves can improve soil fertility, but the timing of grazing and crop rotation need to be monitored regularly to avoid exceeding grazing targets. Adding trees to pastures (silvopasture) increases soil carbon content and provides shade for livestock. Planting fruit trees and timber species can increase revenues from the operation; improve dairy yields by protecting animals from wind and extreme temperatures; decrease evaporation of soil moisture, which delays senescence of plants on which livestock feed; and attract a greater number of native species.

Biological and physical sciences indicate that regenerative practices can prevent erosion, retain soil moisture, and increase carbon sequestration (Paustian et al. 2020), but there are few quantitative data on the potential magnitude of these benefits. Furthermore, the amount of carbon sequestered per unit area varies among regions, crops, and producers; may not be permanent; and can be scientifically and logistically difficult to verify (Ranganathan et al. 2020). Adoption of regenerative practices requires an understanding of fundamental ecosystem processes and changes in human behavior and norms, and the process of learning to manage agricultural systems without using chemicals can be slow (Gosnell et al. 2022).

In Oregon, several organizations are promoting the expansion of regenerative practices across the state. For example, the Oregon Climate and Agriculture Network (ORCAN) is contributing to existing educational programs for farmers; strengthening networks with diverse stakeholders, from farmers to policy makers; advocating to improve soil conditions; advising the Oregon Global Warming Commission; and contributing to development of legislation. The Healthy Soils Healthy Climate Act (S.1356; www.congress.gov/bill/117th-congress/senate-bill/1356?s=1&r=45), introduced in April 2021 by Oregon senator Ron Wyden, would amend the Food Security Act of 1985 to create a permanent soil health program within the U.S. Department of Agriculture's Environmental Quality Incentives Program. Each year, $100 million would be allocated for incentive payments to producers who adopt practices designed to increase carbon levels in soil. Additionally, the bill would establish protocols for measuring soil organic carbon levels before and after implementation of such practices. The bill also would provide grants to land-grant colleges and universities to conduct research on soil health and carbon science and facilitate research on these topics at U.S. Department of Agriculture research stations.

The Agriculture Resilience Act (S.1337; www.congress.gov/bill/117th-congress/house-bill/2803/text) was introduced in April 2021 by Representative Chellie Pingree of Maine and Senator Martin Heinrich of New Mexico. The bill sets a goal of the U.S. agricultural sector achieving net zero emissions of greenhouse gases by the year 2040. It emphasizes increasing investments in agricultural research, improving soil health, supporting the transition to pasture-based livestock, ensuring farmland preservation and viability, promoting on-farm renewable energy, and reducing food waste.

Portland-based Sustainable Northwest, a 501(c)(3) nonprofit organization, recently received about half a million dollars from the M.J. Murdock Charitable Trust for a regenerative ranching program in Wallowa County in partnership with Country Natural Beef, a cooperative of more than 100 family

ranches that manages 26,000 km^2 (10,000 mi^2) in the western United States. Sustainable Northwest also received $10 million from the U.S. Department of Agriculture to invest in carbon sequestration, improvement of water quality, and protection of wildlife habitat at 120 beef operations across nine states. Emissions from each ranch will be monitored with the goal of reducing the net carbon emissions of beef production by 50–100 percent compared to convention operations.

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