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Drought impacts on the electricity system, emissions, and air quality in the western United States

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The western United States has experienced severe drought in recent decades, and climate models project increased drought risk in the future. This increased drying could have important implications for the region's interconnected, hydropower-dependent electricity systems. Using power-plant level generation and emissions data from 2001 to 2021, we quantify the impacts of drought on the operation of fossil fuel plants and the associated impacts on greenhouse gas (GHG) emissions, air quality, and human health. We find that under extreme drought, electricity generation from individual fossil fuel plants can increase up to 65% relative to average conditions, mainly due to the need to substitute for reduced hydropower. Over 54% of this drought-induced generation is transboundary, with drought in one electricity region leading to net imports of electricity and thus increased pollutant emissions from power plants in other regions. These drought-induced emission increases have detectable impacts on local air quality, as measured by proximate pollution monitors. We estimate that the monetized costs of excess mortality and GHG emissions from drought-induced fossil generation are 1.2 to 2.5x the reported direct economic costs from lost hydro production and increased demand. Combining climate model estimates of future drying with stylized energy-transition scenarios suggests that these drought-induced impacts are likely to remain large even under aggressive renewables expansion, suggesting that more ambitious and targeted measures are needed to mitigate the emissions and health burden from the electricity sector during drought.

drought | electricity system | air quality | climate change

Significance

Climate-driven changes in drought could disrupt electricity systems that depend heavily on hydropower, potentially increasing generation from fossil fuel sources. Impacts from the associated emissions and air pollution could represent a large and unaccounted-for social cost of climate change. We empirically quantify the impacts of drought on fossil fuel power plants in the western United States and the consequent effects on emissions and air quality. Damages through these channels are estimated to be 1.2 to 2.5x the increase in direct economic cost of drought-induced fossil fuel electricity generation. Under future climate, these drought-induced impacts likely remain large due to increasing drought risks, and we find that even rapid expansion of renewable energy has limited ability to curb these impacts.

Climate change can influence energy systems by altering energy supply, demand, and transmission, leading to significant economic and environmental impacts (1–5). For instance, existing work highlights how a changing climate will affect electricity demand and energy expenditure (6, 7), how it can influence how much of a given energy source (e.g., hydropower) can be utilized (8–10), and how it can influence the operations of thermal power plants (11). Many of these insights are then incorporated into energy system models to estimate the overall impacts of climate change on the energy supply, demand, and system cost (12).

Yet the overall societal costs of climate-related disruptions to the energy system could extend beyond the channels explored in existing work. In particular, climate disruptions could result in increases in electricity generation from fossil fuel sources if a changing climate induces large changes in energy demand and/or supply, as existing work suggests, and if marginal electricity generation source used to cover short-run increases in demand or decreases in supply remains reliant on fossil fuels. Increased fossil generation could then result in increased greenhouse gas (GHG) and air pollutant emissions, with emissions increases perhaps occurring far from the location of the climate shock, given the spatially interconnected nature of many energy systems. The associated economic and health impacts of these climate-induced emissions are often unaccounted for in existing analyses.

In this paper, we study the impacts of drought on the electricity system and the consequent effects on GHG emissions, air quality, and human health in the western United States. Drought could influence the electricity generation and emissions of fossil fuel power plants through a variety of compounding pathways. Drought reduces runoff and electricity generation from hydropower (12, 13), while accompanying heat waves can influence electricity demand (14, 15). Accompanied weather patterns during drought can also influence electricity supply from nonhydro renewable energy sources, e.g., drought-induced wildfire smoke could reduce solar generation (16), which can then influence generation and emissions from fossil fuel plants. As many fossil fuel plants require extensive amounts of cooling water, a scarcity of cooling water can also decrease the operating efficiency and electricity supply from those impacted plants (11, 14, 17).

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More importantly, when multiple regions are connected through the electricity transmission networks, drought conditions in one region can lead to changes in generation from fossil fuel plants in another region (18, 19). These multiple pathways between drought and operation of fossil fuel plants make it difficult to understand the emission and air quality impacts of drought on the electricity system ex ante.

In this paper, we focus on the 11 US states which are connected to the Western Interconnection. The western United States has experienced record-breaking drought conditions since 2000 and a declining trend in total runoff (Fig. 1*A*), influenced by anthropogenic climate change (20, 21). Reduced runoff has substantial implications for the electricity system in the western United States, given that hydro accounts for 23% of the electricity generation in this region (22) and that there is a very close coupling between runoff anomalies and hydro generation (Fig. 1*B*). The western United States faces significant challenges under a changing climate as climate models project significant increases in drought risks due to increased co-occurrence of high-temperature and low-precipitation conditions (20, 23). Despite having lower air pollutant and GHG emissions per unit of electricity generation compared to the rest of the United States, 60% of the regional electricity supply still comes from over 800 fossil fuel power plants, including 108 coal or oil-based power plants with high CO_2, SO_2, and NO_x emissions (Fig. 1*C*).

Recent droughts in this region have attracted wide attention (18, 24–28), but much less is understood about the potential impacts on emissions, air quality, and human health. Using energy system models or state-level data analysis, a few studies have found significant increases in CO_2 emissions from the power sector during drought (25, 26, 29, 30). Very few studies have quantified the impacts of drought on air pollutant emissions from fossil fuel plants, and these estimates are often aggregated at the regional or state level (30, 31). Accurate accounting for the emissions and health impacts of drought-induced fossil fuel generation is challenging as it needs to account for both the heterogeneous responses across different power plants as well as transboundary impacts through the interregional exchange of electricity. Future policy and investment would also benefit from projections of the emissions impacts under future climate and transitions in the electricity sector (e.g., expansion of renewable energy); however, there exist no studies conducting such projections using empirically grounded relationships.

Here, we estimate the impacts of drought on electricity generation and emissions from fossil fuel plants in the western United States and the associated air quality and health effects, using empirical data on plant-level generation and emissions, runoff, and observational air quality measured by surface monitors from 2001 to 2021. Our analysis directly accounts for the transboundary impacts of drought on fossil fuel generation and pollutant emissions, due to the import/export of electricity across three electricity regions (Fig. 1*C*, following definitions of the Energy Information Agency). We first develop a statistical model between plant-level electricity generation and runoff anomalies in each of the three electricity regions. As drought impacts on individual fossil fuel plants vary as a result of their operational status, locations, and fuel type, we estimate drought impacts at a disaggregated level—specifically on each set of power plants that are located in the same electricity balancing–authority area and use the same fuel type. For each plant, we then calculate the drought-induced generation, defined as the changes in generation as a result of the runoff anomalies (relative to the 1980 to 2021 average).

To estimate the impacts on air quality and related health damages, we quantify the changes in measured surface $PM_{2.5}$ that are attributable to drought-induced changes in SO_2 and NO_x emissions from fossil fuel plants. We specifically focus on

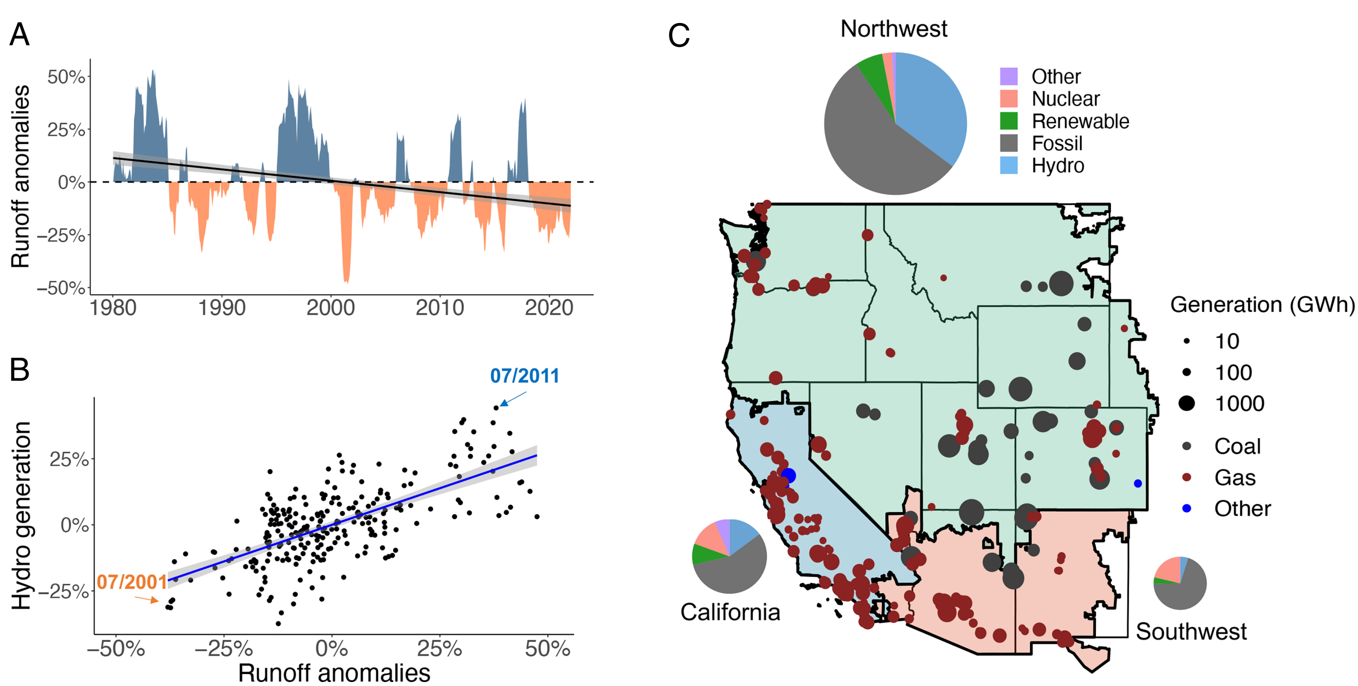

Fig. 1. Drought conditions and the electricity system in the western United States. (*A*) The declining trend of regional runoff anomalies of the western United States from 1980 to 2021. (*B*) Relationship between monthly hydro generation anomalies (deviations relative to the monthly mean) and monthly runoff anomalies in the western United States. (*C*) fossil fuel power plants in the western United States in our sample during the studied period (2001 to 2021). The western United States is divided into three electricity regions: California (CA), Northwest (NW), and Southwest (SW). Pie charts in *C* show the percentage of electricity generation from different generating technologies, averaged over 2001 to 2021 (the size of the pie is proportional to the total electricity generation in each region).

surface $PM_{2.5}$ that is not related to wildfire smoke, as wildfire is more prevalent during drought periods and it contributes substantially to surface $PM_{2.5}$ (*Materials and Methods*). We quantify whether predicted drought-induced emissions affect surface $PM_{2.5}$ concentration measured at nearby air pollution monitors. We then calculate the monetized damages from excess mortality due to observed $PM_{2.5}$ changes using an empirically derived concentration–response function (CRF) that relates short-term changes in air pollution to mortality (32) and a value of statistical life of $10.95 million (year 2019 dollars) recommended by the US EPA (33). We further quantify the monetized damages of drought-induced GHG emissions by accounting for increased CO_2 emissions using the social cost of carbon ($117 per ton, year 2020 dollars) (34) and methane (CH_4) leakage using a 2.3% leakage rate across the life cycle of the gas production and usage (35) and the social cost of methane ($1257 per ton, year 2020 dollars) (34).

Finally, to assess potential impacts under future climate and energy production scenarios, we combine our empirical estimates of plant-level emission changes with climate projections and stylized electricity sector scenarios. We use the average 2030 to 2059 projected runoffs from The Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model ensemble. We consider three potential scenarios in the electricity sectors using results from existing energy system model projections (36, 37): replacing coal power plants with natural gas plants, increased penetration of carbon capture and storage (CCS), and increased penetration of renewable energy and battery technology. For the renewable energy scenario, we use the "Low Renewable Cost" scenario from the National Renewable Energy Lab's projections of the US electric sector through 2050 (36), which projects the average and marginal energy source in the electricity sector.

Results

Drought Increases Electricity Generation from Fossil Fuel Plants. Compared to the average conditions in 1980 to 2021, the electricity generation from the fossil fuel plants on average increased by 35%, 11%, and 9.5%, in California (CA), Northwest (NW), and Southwest (SW), respectively, in the driest months during the study period (Fig. 2). Importantly, we find that the combined effect of drought on fossil generation across the three regions ("total effect") is substantially larger than the effect of drought on the fossil generation in the same region alone ("local effect"). Increases in fossil generation due to drought conditions occurring in the neighboring electricity regions account for 63% of the total generation increases in CA during the drought periods, along with 44% of the total generation increases in NW, and almost all of the generation increase in SW. As shown in Fig. 2*D–F*, drought occurring in the NW can lead to increases in fossil fuel generation in all three electricity regions, while CA drought leads to increases in fossil fuel generation from power plants in CA and NW. Our estimation results are consistent across alternative specifications of the regression models and models using alternative drought indices, choices of data inclusion criterion, and region definitions (*SI Appendix*, Figs. S2–S5 and Table S1).

The transboundary effects of drought on fossil fuel generation are largely driven by changes in the import/export of electricity

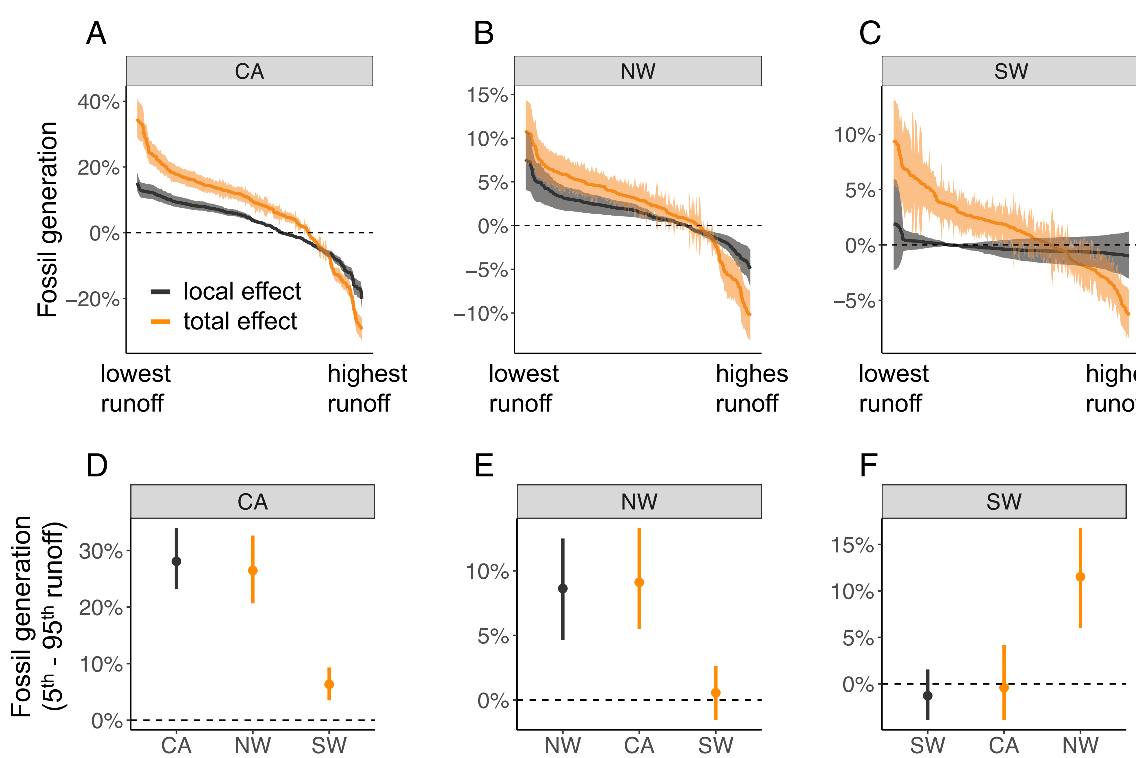

Fig. 2. Drought increases electricity generation from fossil fuel plants with substantial transboundary effects. (*A–C*) Relative changes in monthly fossil generation in each region due to runoff changes in our study period. The *X* axis is sorted by the changes in fossil fuel generation, from months with the lowest runoff on the left to the months with the highest runoff on the right. Black lines show the "local effect" which only accounts for the impact of runoff on power plants in the same region. Orange lines show the "total effect" which accounts for the impacts resulting from runoff changes in all three regions. (*D–F*) Changes in fossil generation in one electricity region (each panel) due to the 5th to 95th percentile change of runoff anomalies (i.e., changes under dry conditions relative to wet conditions) in each of the three regions (*x* axis of each panel). The shades in panels (*A–C*) and error bars in (*D–F*) show the 95% CI of the estimated generation changes.

due to drought-induced supply or demand shocks. Neighboring regions that are connected to the drought regions increase fossil fuel generation from their own plants to make up for shortfall in the drought region. We corroborate these findings using a separate dataset on the import and export of electricity between these three regions (38). For example, when comparing a dry period (with the 5th percentile of runoff anomalies) relative to a wet period (with the 95th percentile of runoff anomalies) in NW, we find a 23% increase of net export of electricity from CA to NW, and a 7.2% increase of net export from the SW to NW (*SI Appendix*, Fig. S6). Magnitudes of the import/export changes are consistent with the transboundary effects of drought-fossil generation quantified above (a 26.4% increase in CA fossil generation due to NW drought and an 11.2% increase in SW fossil generation due to NW drought). These results suggest that when hydropower production is reduced in NW under drought, less power is available for export to either CA or SW, and therefore, fossil fuel plants in CA or SW would need to increase their electricity generation to fill this gap.

To further understand the mechanisms between runoff and fossil fuel generation, we use causal mediation analysis in CA and NW where the "local effects" of drought on fossil generation are significant and substantial (*SI Appendix*, Fig. S7). We find that the need to substitute for changes in hydropower is the leading mechanism that explains the runoff—fossil generation relationship. We find that increases in fossil generation during low runoff periods are not empirically related to the changes in the electricity demand. In the *Discussion*, we briefly discuss the potential reasons and its implications. We further find that a small fraction of the increases in fossil generation could be due to reductions in renewable generation, consistent with the evidence of reduction in solar generation due to wildfire smoke (which often coincides with drought) and the reduction in wind power due to lower wind speed during drought episodes (see *SI Appendix* for more discussions) (39–41). We also find some evidence that the drought-induced emissions from the fossil fuel plants are possibly offset by increases in ambient temperature at the plant locations, suggesting potential generation curtailment due to high-temperature conditions (*SI Appendix*, Fig. S7). To further test whether the hydro displacement is the dominant channel between runoff and fossil fuel generation, we perform a placebo test that applies the same model to Texas and Florida, two electricity regions that are largely isolated from the rest of the country and have little hydroelectricity capacity. There, we find no effects of runoff changes on generation from fossil fuel plants (*SI Appendix*, Table S2).

Drought-Induced Emissions Increase Surface $PM_{2.5}$ Near Fossil Fuel Plants. When accounting for the plant-level heterogeneity, we find that drought-induced emissions account for ∼12% of the total regional CO_2 emissions from the electricity sector, ∼6% of the total NO_x emissions, and ∼8% of the SO_2 emissions during extreme drought periods (e.g., spring and summer during 2001). Relative changes in SO_2 and NO_x emissions are smaller than CO_2 emissions due to the relatively small impacts of drought on the large high-emitting coal power plants. However, some individual power plants experience larger changes in SO_2 and NO_x (Fig. 3*A*). For example, in an extremely dry year like 2001, we predict that roughly 20% of plants would increase their SO_2 and NO_x emissions by at least 30%; this increase is more than triple the regional average increase for all plants. These results highlight the substantial local heterogeneity in emissions impacts from a common regional drought shock.

Drought-induced emissions of SO_2 and NO_x from fossil fuel plants increase surface $PM_{2.5}$ near the power plants (in

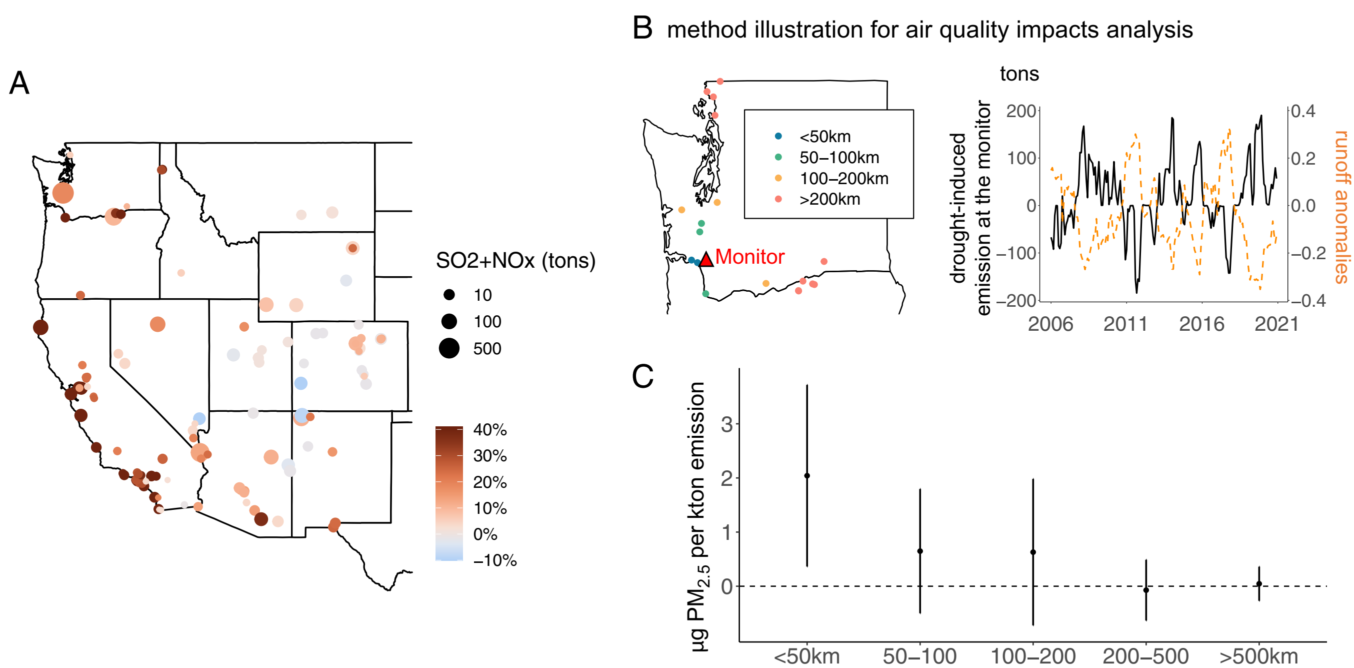

Fig. 3. Drought-induced emissions increase nearby surface $PM_{2.5}$ concentration. (*A*) Predicted drought-induced emissions (SO_2 + NO_x) from each fossil plant due to runoff anomalies in 2001, an extremely dry year. Colors show the percentage changes relative to the total plant emissions in 2001. (*B*) Illustration of our method to quantify impacts of drought-induced emissions on $PM_{2.5}$ concentration measured at surface air quality monitors, using a specific monitor in Washington as an example. For each monitor, we calculate total drought-induced emissions from all fossil fuel plants within a given distance of the monitor (e.g., 100 km) and quantify the impacts on surface air quality due to changes in emissions within that distance. (*C*) shows the impacts of drought-induced emission from power plants in each distance bin on surface $PM_{2.5}$ measured at the monitors (the bars show the 95% CI).

particular, within a 50-km radius), while, as expected, the effects gradually decay as the distance between the monitor and power plant increases (Fig. 3*C*; also see *Materials and Method* and Fig. 3*B* for method illustrations). We also find evidence that suggests that increases in surface $PM_{2.5}$ are more likely to be associated with drought-induced emissions from plants at the upwind location of the monitor, further strengthening our causal claims (*SI Appendix*, Fig. S8). Our estimation results are largely robust to alternative specifications of fixed effects, specification of regional air quality trends, and meteorology controls (*SI Appendix*, Fig. S9). We also calculate the $PM_{2.5}$ impacts using the reduced-complexity air quality model, the Intervention Model for Air Pollution (InMAP) (42). Using the same set of drought-induced emission, InMAP also estimates a increase in surface $PM_{2.5}$, although with a substantially smaller magnitude than our empirically derived estimates (*SI Appendix*, Fig. S10 and *Discussion*).

Monetized Economic and Health Impacts of Historical Droughts. We value the total health and economic damages of drought-induced fossil electricity generation by monetizing the impact of predicted changes in air pollution, CH_4 leakage, and CO_2 emissions when drought strikes, applying our estimates backward over the observed drought time series (Fig. 4*A*). As most of the recent 20-y period is drier than the 1980 to 2021 long-term average, we calculate that the western United States has experienced a total net damage of \$20 billion during this period. Drought-induced CO_2 emissions account for \$14 billion, or 70% of the total damage. $PM_{2.5}$-associated mortality accounts for \$5.1 billion (25% of the total damage) and CH_4 leakage accounts for \$1.0 billion (5% of the total damage).

Despite the consequential total damage from recent historical droughts, annual damages declined markedly after 2001. This is largely driven by the declining emission factor of fossil fuel electricity generation (i.e., emissions of NO_x, SO_2, and CO_2 per unit of electricity generation) over the last 20 y (Fig. 4*B*). NO_x and SO_2 emission factors in the western United States have declined by eight- to ten-fold primarily due to the transition from coal to natural gas and the installation of scrubbers (44, 45). The CO_2 emission factor also declined by 40%—a magnitude smaller than SO_2 or NO_x since natural gas plants are still significant carbon emitters and policies rarely target the stack-level emissions of CO_2 within the fossil fuel plants.

We find that installation of scrubbers at high-emitting plants near the population centers leads to marked reduction in the $PM_{2.5}$-related health damages. For example, one power plant (which includes two coal-fired units) in Washington state was responsible for 26% of the total drought-induced $PM_{2.5}$ damage in 2001 in the western United States (*SI Appendix*, Fig. S11). However, drought-induced $PM_{2.5}$ damages associated with this plant decreased by 90% after the installation of scrubbers in 2002, contributing to a large part of the decline in total $PM_{2.5}$ damage. In the more recent years (e.g., 2018 to 2021), most of the monetized damages of the drought-induced fossil generation come from CO_2 emissions (84% of total damage), while $PM_{2.5}$-related health damage and the CH_4 leakage each accounted for 10% and 6% of the total damage.

These monetized damages exceed estimates of the economic impacts of drought on the electricity system reported by previous studies (27, 28). As a point of comparison, we focus on the 2012 to 2016 drought in California, a period which has been extensively studied (Fig. 4*C*). Both Kern et al. and Gleick quantified the increase in total cost of electricity generation due to the switch from low-cost hydro generation to more expensive fossil fuel generation. Kern et al. also examined the extra cost due to increased electricity demand and the potential influence

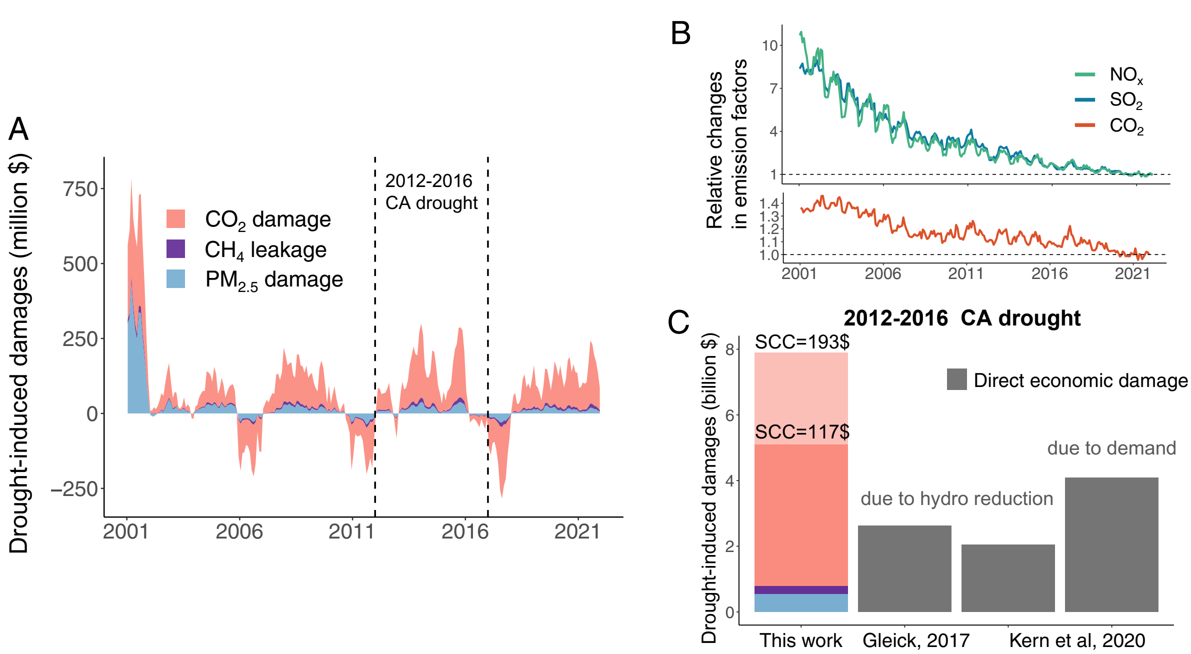

Fig. 4. Monetized economic and health impacts of drought-induced fossil fuel generation. (*A*) Monetized damages from extra CO_2 emissions, CH_4 leakage, and $PM_{2.5}$-related mortalities, due to runoff changes (relative to the 1980 to 2021 average). Monetized values are calculated using a social cost of carbon value of \$117 per ton, a social cost of methane value of \$1,257 per ton (year 2020 dollars) from US EPA (34), and a value of statistical life of \$10.95 million per mortality (year 2019 dollars). (*B*) Declines in annual monetized damages over time are a result of declining emissions factors (i.e., emissions per unit energy production) over the western United States (2021 values are normalized to 1). (*C*) Total damages of the 2012 to 2016 drought in California, compared to estimates of the direct economic impacts from the prior literature due to reductions in hydropower and the increased electricity demand (27, 28). CO_2 damages are calculated using two SCC values, \$117 per ton as in *A* and \$193 per ton (under a 2% discount rate following ref. 43). In *C*, we only calculate the impacts originating from fossil fuel plants in CA and impacts in other regions due to the runoff changes in CA.

of higher natural gas prices on generation costs. We account for drought-induced damages associated with emissions from power plants in CA as well as damages in the other two regions as a result of the CA drought. We estimate that the drought-induced CO_2 emissions account for 19% of the total electric CO_2 emissions in CA during this period (11% from CA plants and 8% from the other two regions). The drought-induced fossil generation led to a total monetized damage of $5.1 billion (using SCC value of $117)—1.2–1.9x of the reported direct economic cost due to the reduction in hydropower and 2.5x of the direct economic cost due to the drought-induced increase of electricity demand (27, 28).

Projecting Future Damages. Despite the variability in projected runoffs across climate models, most models project increasing or sustaining drought risks over the western United States during 2030 to 2059 relative to 1980 to 2014 (*SI Appendix*, Fig. S12). Averaged across climate model projections under the reference scenario [assuming no changes in the electricity sector under a high climate-forcing scenario (SSP3-7.0)], drought-induced fossil fuel generation could result in annual damages of $293 million (relative to 1980 to 2014 averages of each model, discounted back to 2020). Damages due to extra CO_2 emissions account for 81% of the total damages, while CH_4 leakage and $PM_{2.5}$ damages account for 8% and 11%, respectively (Fig. 5*A*).

These drought-induced economic and health damages, however, could be substantially lower under the alternative climate scenarios with lower GHG emissions (SSP1-2.6 and SSP2-4.5). Compared to SSP3-7.0, we estimate a reduction in annual damages by $214 million under SSP2-4.5 or 73% of the damages under SSP3-7.0 (Fig. 5*B*). This reduction is primarily driven by the higher projected runoff in California and Northwest projected by models under the two lower GHG scenarios. We find that the damages under the SSP2-4.5 scenario are lower than the SSP1-2.6 scenario, likely due to the nonlinear relationship between runoffs and the GHG forcings and model uncertainties. Runoff generally decreases under higher air temperature due to the increased evapotranspiration (23, 46), but the substantial uncertainty in precipitation and the role of vegetation further complicates the runoff responses across different climate scenarios (47, 48).

Surprisingly, the projected transitions in the electricity sector have modest effects in mitigating the damages from the drought-induced fossil generation, with the only exception of expansive penetration of CCS in 2050 (see Fig. 5*C* for the result of 2050, and *SI Appendix*, Fig. S13 for the result of 2035). Relative to the reference scenario under SSP3-7.0, replacing all coal power plants with natural gas plants only reduces drought-induced damages by 11%. Increased penetration of renewable energy and energy storage has an even smaller impact—a reduction in the damages by 5.4% in 2050. These modest effects are in sharp contrast with the total emission mitigations that could be achieved under these two strategies. Total CO_2 emissions from the fossil fuel plants would decline by 72% under the same *high RE* scenarios and by 26% under the *coal-phase out* scenario, respectively. These disparities are due to the differences between the projected changes in *marginal* energy sources (i.e., those sources used to cover short-run increases in demand or decreases in supply) and *overall* energy sources (i.e., those sources used to meet overall average demand) in the future (*SI Appendix*, Fig. S14). For example, fossil fuel generators are projected to only generate 8.6%

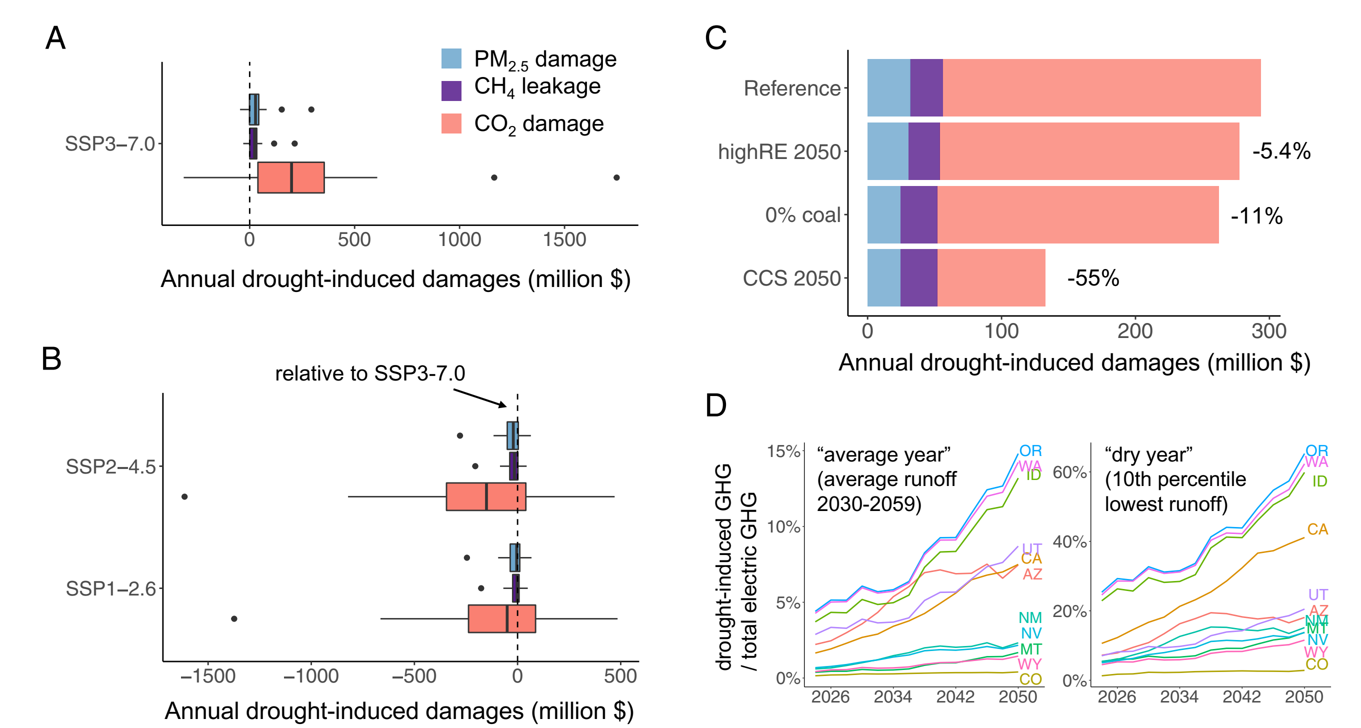

Fig. 5. Future damages of drought-induced fossil generation could be mitigated under low GHG scenarios and lower-carbon electricity sector scenarios. (*A*) Annual drought-induced damages projected by 33 climate models under the SSP3-7.0 scenario over 2030 to 2059 (relative to the 1980 to 2014 average of each model). (*B*) Declines in monetized damages under low GHG scenarios (SSP1-2.6 and SSP2-4.5), relative to the SSP3-7.0 scenario. (*C*) Projected electricity sector transitions reduce drought-induced damages at varying magnitudes (mean values of the 33 models under the SSP3-7.0). (*D*) Increasing importance of the drought-induced GHG emissions relative to the total GHG emissions from the electricity sector, under the *high RE* scenario. GHG emissions included the CO_2 emissions and potential CH_4 leakage (aggregated using the global warming potential of 100 y). Drought-induced emissions are calculated using the average runoffs in 2030 to 2059 (*Left* panel, "average year") or the 10th percentile lowest runoffs during 2030 to 2059 (*Right* panel, "dry year").

of the total electricity in California in 2050 (compared to 41% in 2021), while they are still projected to be the dominant marginal energy source used to meet demand fluctuations, serving as the marginal source in the grid for 71% of the year. As a result of the differential changes between the overall and marginal energy sources, we estimate that the relative contributions of drought-induced GHG emissions will increase by two- to fourfold in many western states over the next 30 y with increasing expansions of renewable energy (Fig. 5*D*). For example, drought-induced GHG emissions of California associated with an extreme drought year (defined as the 10th percentile lowest runoffs during 2030 to 2059) would account for 41% of the total electricity GHG emissions of California in 2050 (compared to only 11% in 2024).

Discussion

By empirically linking runoff variability to plant-level generation, emissions, and surface $PM_{2.5}$, our analysis quantifies the environmental and economic impacts associated with drought-induced fossil fuel generation. In the states that heavily rely on hydropower for electricity generation, drought-induced GHG emissions could account for up to 40% of the total electricity emissions of those states during future extreme drought years. Our analysis suggests that the impacts of drought on the electricity system have been underestimated by previous research that largely focuses on the direct economic costs of drought-induced disruptions to the electricity sector.

We find that over 50% of the drought-induced fossil fuel generation—and the resulting economic and health damages—is transboundary. Previous studies have shown that the interregional connection could mitigate drought-induced risks in terms of grid stability and generation cost (19). Our analysis however demonstrates that the drought-induced emissions impacts could be redistributed through the grid interconnection, consistent with findings from prior work (30). More broadly, our results have important implications for research that uses empirical or statistical models to quantify the impacts of climate or other environmental change. Our analysis suggests that, at least in some settings, local economic and health impacts could be driven by distant climate change and that a careful empirical strategy is needed to uncover these teleconnections.

Drought-induced economic and health damages from fossil fuel generation will remain an important challenge under future climate. However, these damages could be substantially reduced under mitigation scenarios which limit the warming level. Surprisingly, we find that increased penetration of renewable energy has a limited effect in reducing drought-induced damages despite a significant reduction in the total fossil fuel generation under the evaluated scenario. This is largely because the amount of renewable energy projected to be deployed under the National Renewable Energy Laboratory scenario displaces a significant fraction of fossil fuel generation on average, but is not yet sufficient to fully replace fossil fuel as the marginal energy source. The drought-induced fossil fuel generation and associated damages will become increasingly important with the overall grid decarbonization. In other words, the electricity sector will become harder to be "fully decarbonized" if we account for the increasingly frequent drought shocks and the associated GHG emissions in systems with at least some hydro. Our research suggests that accounting for the impacts of climate change and its variability on the electricity system is important for decarbonization in the western United States; such factors have been studied in some scenario analyses (49, 50) but not fully integrated in most decarbonization scenarios.

We show that drought conditions could further exacerbate ambient $PM_{2.5}$ pollution, a leading environmental risk factor around the world, through heavier usages of fossil fuels in the electricity system. More broadly, our analysis contributes to a better quantification of the impacts of climate change on human health through climate-induced changes in air pollution. Our work contributes to an emerging literature that climate change can influence air quality through influencing fossil energy usage (51), extending the focus beyond the impacts on naturally induced emissions (such as through wildfire) or the chemistry/meteorology channels (52–55).

Our analysis contributes important insights to the measurement of air quality impacts of emission changes associated with environmental shocks or policies. We find that our empirical estimates of the $PM_{2.5}$ impacts differ from the results simulated by InMAP in many important ways. Our empirical method estimates a larger response of $PM_{2.5}$ to precursor emission changes near the plants but virtually no effect outside the 200-km radius [consistent with prior empirical analysis (45)]. Our empirical estimates are consistent with previous studies that show that InMAP underestimates the $PM_{2.5}$ concentration (or the $PM_{2.5}$-emission sensitivities) in the western United States either comparing to the surface $PM_{2.5}$ monitors (56) or the full-complexity chemical transport model (57). More research is needed to better understand the strengths and limitations of estimating impacts of emissions changes on air quality with both the empirical method as well as process-based air quality models.

Our research reveals multiple pathways for future research to better understand the impacts of drought on the energy systems and associated downstream impacts. In this work, we use the cumulative runoff in the previous 9 mo to characterize drought conditions as it is more directly related to hydropower [compared to standard drought indices such as the Palmer Drought Severity Index (58)]. Therefore, our analysis is designed to capture the relatively longer-term impacts of the "hydrological drought" on the electricity system. As the long-term runoff changes are only partially correlated with temperature variations, our analysis, therefore, only partially captures the effects of the accompanying heat waves on electricity demand and the associated generation from fossil fuel plants. Future studies could build on our empirical framework to directly incorporate the influence of heat waves.

The quantified economic and health damages of drought-induced fossil emissions, while substantial, are likely a lower bound of the full impacts of drought on the electricity system. Our analysis does not capture the potential economic and health impacts of drought-induced blackouts [especially if they overlap with dangerous heat waves (59)]. Our estimates also do not explicitly account for the fluctuation of fuel prices (especially natural gas) which can be an important factor for the economic impacts of drought-induced disruptions (27). Also, we only quantify the impacts on the fossil fuel plants that are connected to the grid due to the data availability. However, drought-induced decreases in hydropower could also increase the usage of backup generators that are not connected to the grid, as well as nonelectricity energy sources especially in other parts of the world (60). Future research is needed to estimate and integrate the impacts that could occur through these various pathways, both in the western United States and in settings outside the United States where these other pathways (e.g., blackouts) could represent more substantial sources of economic loss.

While our study has focused on the western United States, our method and findings are globally relevant as many countries that heavily rely on hydro power have experienced increasing drought risk due to climate change. Globally, we identify 19 countries that are potentially vulnerable to drought-induced shocks to their electricity and energy system (*SI Appendix*, Fig. S15), primarily located in Central and South America, Africa, and South East Asia. These countries heavily depend on hydropower for their electricity generation (>20% of the annual electricity generation) and could potentially experience increasing drought risks as projected by the climate models (>5% decline in the average 2030 to 2059 runoff, the median across different climate models). For example, Honduras relies on hydropower to provide 53% of the nation's electricity and is projected to experience a 20% decrease in runoff by midcentury under SSP3-7.0. Electricity systems in many countries are more polluting compared to the western United States (with a more coal-dominant grid) and can therefore lead to higher economic and health damages due to deteriorated air quality and GHG emissions (61, 62). Furthermore, drought-induced reductions of hydropower could result in blackouts in countries that do not have enough excess electricity generating capacities, leading to further economic or health consequences (63, 64). Better understanding drought-related impacts on the energy systems and consequent environmental and economic damages in a global sample of countries is an important avenue for future research.

Materials and Methods

Unit-Level Generation and Emissions Data. Our analysis focuses on the western United States which spans three Energy Information Agency (EIA) electricity regions: California (CA), Northwest (NW), and Southwest (SW) (38). See *SI Appendix* for results under alternative region definitions. Hourly electricity generation and emissions (CO_2, SO_2, and NO_x) of major fossil fuel electricity generating units (nameplate capacity >25 MW) are obtained from the EPA Air Market Program Data from 2001 to 2021 (65). We aggregate hourly emissions and generation to a monthly level for each unit. Unit-level characteristics such as location, primary fuel type, and stack height are derived from the EPA Emissions & Generation Resource Integrated Database (66). In our main analysis, we only include an observation (i.e., unit-month) if the unit has at least four non-missing values during the month (see *SI Appendix* for more details on the sample restrictions). Our final sample consists of 95,608 unit-months from 681 electricity generating units–586 units that use natural gas, 91 units that use coal, and four units that use biomass or other fuel types. Our final sample covers 90% of electricity generation from fossil fuel plants (including biomass), and 49% of the total generation in the 11 states of the western United States in 2019 (66) (nonfossil generation includes generation from hydro, nuclear, wind, and solar energy). We perform a sensitivity analysis to examine the effects of runoff changes on generation from fossil fuel plants that are not in our main sample ("non-AMPD" plants) and find that the estimated drought-induced generation from the non-AMPD plants is 7.3% of our main estimates (*SI Appendix*, Table S3 and *SI Appendix*).

Drought Characterization. Following Herrera-Estrada et al. (30), we use the total runoff (sum of surface and subsurface runoffs) to characterize drought conditions. Previous studies have shown that runoff more accurately captures hydrological drought and the influence on hydropower compared to other standardized drought indices (e.g., the Palmer Drought Severity Index) (30, 67). We use monthly runoff data from the VIC land-surface model of phase 2 of the North American Land Data Assimilation System (NLDAS-2) (68), following recommendations from the prior literature (30, 69). For each electricity region, we first calculate the state-level runoff averaged over grid cells in each state and then calculate the regional runoff as a weighted average of state-level runoff (weighted by the state-level hydropower capacity). To capture the long-term dynamics of hydrological drought, we calculate the running average of runoff for the previous 9 mo. The runoff anomalies are then calculated as the relative deviations from the 1980 to 2021 average for each region and month of year. We find largely consistent results when using runoff values calculated with different averaging windows and values from the other NLDAS-2 models (*SI Appendix* and *SI Appendix*, Fig. S2). We also find similar results using a distributed lag model (*SI Appendix*).

Empirical Strategy: Impacts of Drought on Fossil Fuel Generation. We estimate the following regression to quantify the impacts of drought on electricity generation from fossil fuel units, while accounting for the cross-regional impacts:

$$y_{igym} = \sum_{k \in \{CA, NW, SW\}} \{\beta_{gk} Q_{kym}\} + \gamma_g \boldsymbol{X_{igym}} + \eta_g y + \psi_{gm} + \theta_i + \epsilon_{igym}, \quad [1]$$

where y_{igym} denotes the log of electricity generation from unit i in electricity region g, year y, and month of year m. Q_{kym} denotes the runoff anomalies of region k in year y and month of year m. Separate equations are estimated for each electricity region g ($g \in \{CA, NW, SW\}$). β_{gk} are the parameters of main interest here, which estimate the causal impacts of change in runoff anomalies in region k on the generation from fossil fuel units in region g, conditional on the runoff anomalies in the other two regions. $\boldsymbol{X_{igym}}$ denotes the regional- and unit-level variables including monthly sales of electricity (i.e., electricity demand), generation of wind power and solar power, and the monthly average air temperature at the plant location. When estimating impacts of drought on fossil generation in the same region ($g = k$), $\boldsymbol{X_{igym}}$ captures possible mechanisms through which runoff could influence fossil generation, and therefore in our main analysis, we report estimates without control variables (see below for the mechanism analysis). While estimating drought impacts on generation from the neighboring regions ($g \neq k$), we report estimates with these variables as controls, as they are not likely to represent the underlying mechanisms.

Our main specification includes linear year trend (y), month-of-year fixed effects (ψ_{gm}), and unit-level fixed effects (θ_i) to control for the underlying trend and seasonality in fossil generation and runoff as well as the time-invariant unobserved factors at the unit level. Our model exploits the deviations in runoff relative to the month-of-year averages (i.e., was it a particularly dry or particularly wet June relative to the regional averages for June conditions) to estimate the effects on fossil fuel generation. ϵ_{igym} represents the error term. β_{gk} are estimated using the weighted ordinary least square approach, weighted by the unit-level monthly average generation. SEs of the regression coefficients are clustered at the plant level. See *SI Appendix* for more details on the alternative specifications of the regression models.

To account for the heterogeneous impacts of drought on different fossil fuel plants, we further estimate Eq. **1** at the Balancing Authority (BA) $\times$ fuel type level. We separately estimate the regression equations for each group of power plants with the same fuel type in the same BA region. In total, we estimate 54 equations for the 54 BA-fuel subgroups. Resolving the impacts of drought on plant generation at a more disaggregated level is important for the air quality and health impact analysis as one unit of emissions could have different impacts on human health depending on their proximity to population centers. For a small number of units (11 out of 681 units), we use the pooled regression coefficients at the regional level instead of coefficients estimated at the BA-fuel level. (For these 11 units, the estimated displaced generation would exceed their total generation if we use the coefficients from the BA-fuel regressions.) The aggregated impacts on electricity generation are consistent across the regressions at the regional or the BA-fuel level (*SI Appendix*, Fig. S16).

Mechanisms of Drought Impacts on Power Plants: Causal Mediation Analysis. We use causal mediation analysis to identify the mechanisms through which runoff changes influence the electricity generation from fossil fuel plants. For the mediation analysis, we only focus on the drought impacts on fossil fuel plants in the same electricity region (i.e., the local effect) and only focus on CA and NW where the estimated local impacts are substantial. Mechanism analysis on the cross-boundary impacts is discussed in a separate section in SI addressing the changes in the import/export of electricity. Causal mediation analysis is a widely used statistical technique across many disciplines that aims to estimate the causal effects of the treatment variable (in our case, runoff) on the outcome variable (in our case, fossil plant generation) through certain causal mechanisms (70). We focus on the following pathways through which drought could influence electricity generation from fossil fuel plants: 1) through changes in hydropower output, 2) through changes in electricity demand, 3) through changes in wind or solar power production, and 4) through changes in the cooling efficiency of thermal power plants due to ambient temperature. More details of the causal mediation analysis can be found in *SI Appendix*.

Air Quality Impacts. We estimate an empirical model between predicted drought-induced fossil plant emissions and surface $PM_{2.5}$ concentration measured by monitors nearby. Using our estimates from the first part of the analysis, we first calculate the predicted drought-induced CO_2, SO_2, and NO_x emission changes at each plant using the following equation:

$$\Delta Emis_{iym} = \sum_{k \in \{CA,NW,SW\}} (e^{(\beta_{ki} \times Q_{kym})} - 1) \times Emis_{iym}, \quad [2]$$

where $\Delta Emis_{iym}$ denotes drought-induced emissions of unit i in year y and month of year m. Q_{kym} denotes the monthly runoff anomaly of electricity region k. β_{ki} denotes the coefficients derived from the BA-fuel level regressions which estimate the impacts of runoff in region k on unit i. $Emis_{iym}$ denotes the observed emissions from unit i in that month. $\Delta Emis_{iym}$ quantifies the changes in emissions due to runoff anomalies relative to the 1980 to 2021 average. $\Delta Emis_{iym}$ can be both positive (when runoff is lower than the 1980 to 2021 average) or negative (when runoff is higher).

Surface $PM_{2.5}$ concentrations are derived from the US Air Quality Systems administered by the US EPA (71). Due to influences of drought on wildfire and associated $PM_{2.5}$ (53, 55), we only use observational $PM_{2.5}$ concentration from monitors on days that are not influenced by wildfire smoke using methods from ref. 72 (see *SI Appendix* for more details). We calculate the monthly average $PM_{2.5}$ concentration for each month and monitor using $PM_{2.5}$ concentration on all nonsmoke days. Our air quality analysis focuses on the period between 2006 and 2020 due to the availability of the wildfire smoke plume data.

We estimate the following regression to quantify the effects of drought-induced emissions on surface $PM_{2.5}$ concentration:

$$PM_{iym} = \sum_{d} \beta_d \Delta Emis_{idym} + \gamma \boldsymbol{W_{iym}} + \eta_y + \psi_m + \theta_i + \epsilon_{iym}, \quad [3]$$

where PM_{iym} denotes the monthly nonsmoke $PM_{2.5}$ concentration measured by monitor i on year y, month of year m, and $\Delta Emis_{idym}$ is the drought-induced emission changes (SO_2 + NO_x) from fossil fuel plants that are located within a certain distance (distance bin d) from the monitor i. For each monitor, fossil fuel plants are grouped into five groups based on their distances from the monitors: <50 km, 50 to 100 km, 100 to 200 km, 200 to 500 km, and >500 km. $\boldsymbol{W_{iym}}$ are the meteorological variables at the location of monitor i. In our main specification, we include the splines of surface temperature, precipitation, dewpoint temperature, boundary layer height, air pressure, 10 m wind direction, and wind speed. Our main specification includes year (η_y) and month-of-year fixed effects (ψ_m) to capture the interannual variability and seasonality of $PM_{2.5}$ concentration and monitor-level fixed effects (θ_i) to control for the time-invarying unobserved factors at the monitor level. ϵ_{iym} represents the error term. β_d are estimated using the weighted ordinary least square approach, weighted by the variance of the inversely distance-weighted drought-induced emissions of each monitor to reduce the uncertainty of the estimates (i.e., observations from monitors are up-weighted if the monitors are closer to plants with substantial changes in drought-induced emissions). SEs are clustered at the state × year × month-of-year level.

To better understand whether the estimated impacts capture the causal impacts of emission changes on surface $PM_{2.5}$, drought-induced emissions are classified into "upwind" or "downwind," depending on whether the fossil fuel plants are at the upwind or downwind direction of the monitor following methods in ref. 73. We find the drought-induced emissions from upwind power plants have a larger impact on surface $PM_{2.5}$ compared to emissions from the downwind power plants, although estimates are somewhat noisy (*SI Appendix*, Fig. S8).

Our main analysis calculates the drought-induced $PM_{2.5}$ using the empirical estimates above and accounts for drought-induced emissions within a 100-km radius. As an alternative strategy to model the air quality impacts, we also use the Intervention Model for Air Pollution (InMAP) to calculate the impacts of drought-induced emissions of SO_2 and NO_x on $PM_{2.5}$ concentrations (see *SI Appendix*, Fig. S17 and *SI Appendix* for more details).

Health Impacts Analysis. We quantify the health impacts of drought-induced fossil fuel generation in terms of the premature mortality associated with changes in $PM_{2.5}$. As we calculate $PM_{2.5}$ changes at the monthly level, we use the concentration–response function (CRF) between mortality and short-term exposure of $PM_{2.5}$ (e.g., at the daily or weekly level), rather than CRFs derived from long-term epidemiological studies. In our main analysis, we use the CRF from the study of Deryugina et al. to quantify the premature mortalities for adults over 65 y old (32). Deryugina et al. estimate that every 1-μg/m^3 increase of $PM_{2.5}$ at the daily level leads to an increase of 0.69 deaths per million people in the following 3 d for adults over 65 y old in the United States. Their study exploits the variation of daily $PM_{2.5}$ due to daily wind direction changes to account for the confounding biases. We calculate the premature mortality among the 65+ age population at the monthly and census tract-level associated with drought-induced changes of $PM_{2.5}$. Population information of different age groups is derived from the 5-y American Community Survey (ACS) data during 2006 to 2010 (74). The health impacts are monetized using a value of statistical life (VSL) of $10.95 million (year 2019 dollars), as recommended by the US EPA (33) and used in previous studies (75). While we use the main estimate of the 3-d window from ref. 32 in our main analysis—as we believe its empirical approach carefully accounts for the confounding biases—we also calculate the health impacts on premature mortality using alternative CRFs from refs. 76–78 and estimates from ref. 32 using different time windows (*SI Appendix*, Fig. S18).

Projecting Future Impacts. We project the future drought-induced electricity generation and emissions (CO_2, NO_x, and SO_2) from fossil fuel plants that are still in operation in 2021, under future climate and electricity sector scenarios. We select the year 2035 and 2050 as our projection points to capture both the potential near-term and medium-term energy transitions.

Future damages are calculated using SCC, SC-CH_4, and VSL adjusted for future climate damages and income growth. These future damages are then discounted back to the year 2020 using a discount rate of 2.5%. For SCC, we use the values of 158$ per ton (emissions year 2035) and 205$ per ton (emissions year 2050). For SC-CH_4, we use the values of 2,313$ per ton (emissions year 2035) and 3,547$ per ton (emissions year 2050). Both values are derived from the latest US EPA report, calculated using a 2.5% discount rate (34). For the air quality impacts, we use the derived empirical relationship between surface $PM_{2.5}$ and drought-induced emissions and project the mortalities using CRFs from ref. 32 and future projected population for the 65+ age group (79). For VSL, we follow a similar method from Carleton et al. (75) to calculate the future VSL values using the projected economic growth in the United States from the OECD-ENV model under the SSP3 scenario (80) and income elasticity of one.

Future Electricity Sector Scenarios. For the electricity sector scenarios, we construct highly stylized scenarios to quantify the impacts of future drought under potential changes in the electricity sector (Table 1). These scenarios are not designed to correspond to any current or proposed policies but rather to reflect potential comparative changes in the electricity system.

We examine the following scenarios: 1) the *reference* scenario which assumes no changes in the electricity sector; 2) the *coal phase-out* scenario which assumes a partial or full phase-out of coal power plants in the electricity grid and retired coal plants are replaced by new natural gas plants; 3) the *CCS penetration* scenario which assumes that some natural gas plants are retrofitted with CCS **on top of** the *coal phase-out* scenario; and 4) the *high RE* scenario which examines the impacts of expanding renewable energy sources and battery technology. For

Table 1. Electricity sector scenarios.

Scenarios	2035	2050
Reference	No change (same as 2021)	No change (same as 2021)
Coal phase-outs	50% coal replaced by average gas plants	100% coal replaced by average gas plants
CCS penetration	10.7% gas generation with CCS	68.5% gas generation with CCS
High RE	calculating using %hours of fossil energy on the margin (derived from the NREL hourly simulation results)	

Note: *Coal phase-out* scenarios assume that the coal power plants are replaced by natural gas plants in the same location. The CCS penetration scenario assumes that some natural gas plants are retrofitted with CCS on top of the *coal phase-out* scenario. The penetration and removal rate of CCS (removal rate: 90%) are derived from the Princeton Net Zero America study (37). The *high RE* scenario uses the hourly simulation outputs from the Cambium data from the National Renewable Energy Laboratory (36), which simulates the marginal energy source for each hour in each Balancing Authority Area.

the *coal phase-out* scenario, we assume 50% of the coal generation in 2035, and 100% of the coal generation in 2050 is replaced by natural gas plants with average emission factors within each region. For the *CCS* scenario, we use the modeling results from the Princeton Net Zero America study (37) which projects the amount of electricity generated using natural gas with and without the CCS technology. Averaged across their four scenarios (*E+, E-, E+RE-, E-B+*), 10.7% and 68.5% of the US gas electricity generation is projected to be generated by plants with CCS technology in 2035 and 2050, respectively.

For the *high RE* scenario, we use the hourly simulation outputs from the Cambium data from the National Renewable Energy Laboratory (36). As the model simulates the marginal energy source for each hour and each Balancing Authority Area, we calculate the time percentage for which the fossil energy is on the margin for each region. We assume that when nonfossil energy is on the margin, the drought-induced electricity gap will be provided by the nonfossil energy and thus results in zero drought-induced emission (see *SI Appendix* for more details).

Future Climate Change Scenarios. For future climate change scenarios, we use the projected runoff values (surface + subsurface) from the Coupled Model Intercomparison Project Phase 6 (CMIP6). We examine three primary climate-forcing scenarios featured by the IPCC, which were constructed as pairs between the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs) (81). We use SSP1-2.6 (which the IPCC refers to as the "Low" scenario), SSP2-4.5 (which the IPCC refers to as the "Intermediate" scenario), and SSP3-7.0 (which the IPCC refers to as the "high" scenario). We use projections from 33 global climate models with available runoff output at the monthly level for the historical and future scenarios (*SI Appendix*, Table S4). Only one ensemble variant is selected for each model—we use the first ensemble variant of each model ("r1i1p1f1") when possible. To be consistent with our empirical analysis, for each climate model, we first calculate the regional monthly runoff values by taking the weighted average of the state-level runoff weighted by the hydropower capacity (capacity is fixed at the 2021 level). We then calculate the 9-mo moving average values for each region and calculate the monthly anomalies relative to the monthly averages derived from the historical simulation (1980 to 2014) of each model. We use the average runoff anomalies from 2030 to 2059, for each climate model and climate scenario.

Data, Materials, and Software Availability. Code and data needed to replicate the results data have been deposited in GitHub (https://github.com/mhqiu/drought-electricity-WUS).

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