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Air quality equity in US climate policy

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The United States government has indicated a desire to advance environmental justice through climate policy. As fossil fuel combustion produces both conventional pollutants and greenhouse gas (GHG) emissions, climate mitigation strategies may provide an opportunity to address historical inequities in air pollution exposure. To test the impact of climate policy implementation choices on air quality equity, we develop a broad range of GHG reduction scenarios that are each consistent with the US Paris Accord target and model the resulting air pollution changes. Using idealized decision criteria, we show that least cost and income-based emission reductions can exacerbate air pollution disparities for communities of color. With a suite of randomized experiments that facilitates exploration of a wider climate policy decision space, we show that disparities largely persist despite declines in average pollution exposure, but that reducing transportation emissions has the most potential to reduce racial inequities.

climate policy | air pollution | environmental justice

Significance

The United States government would like to advance equity through climate policy. As conventional air pollutants are a by-product of greenhouse gas emissions, climate policy may improve historical inequities in air pollution. We quantify how different decision criteria in national policy implementation would impact racial/ethnic air pollution inequities. Although emission reduction will reduce total air pollution, we find that using cost and income as criteria for emission reduction, as is done in contemporary climate policy, can exacerbate inequities. Reducing air pollution disparities is therefore not an inevitable consequence of climate policy. However, removing emissions from regions with the most people of color directly and cutting transportation emissions can reduce air quality inequities.

After rejoining the Paris Climate Agreement in 2021, the United States submitted an updated Nationally Determined Contribution (NDC), providing a vision of how the United States intends to cut greenhouse gas (GHG) emissions in the coming decades. The NDC set a target of 50 to 52% reduction of net GHG emissions by 2030 compared to 2005. Beyond its quantitative targets, the NDC explicitly identifies climate policy as an opportunity for furthering environmental justice goals, stating, "Each policy considered for reducing emissions is also an opportunity to improve equity and support good jobs in the United States" (1). In an effort to meet these targets, the United States recently passed the Inflation Reduction Act (IRA) (2), which promotes emission reduction largely through financial incentives and aims to invest in disadvantaged communities by providing funds for financial and technical assistance for zero-emission technologies, grants for community-led projects, and funding to reduce air pollution where pollution exceeds national standards. Many details for implementation of the IRA are unresolved, making technical strategies for satisfying its objectives particularly salient.

GHG emissions are often coemitted with criteria pollutants, which damage human health (3, 4). These pollutants sometimes consist of, or subsequently form, fine particulate matter ($PM_{2.5}$), which causes and exacerbates a wide variety of other health conditions (5) and leads to more than 100,000 premature deaths in the United States annually (6). It has been repeatedly demonstrated that the burden of air pollution is not experienced equally among demographic groups in the United States (7–9). While reductions in GHG emissions would be expected to improve average air quality, bestowing a wide array of health, economic, and other benefits (10, 11), reductions in air pollution disparities are not guaranteed. While previous studies agree that reductions in GHG emissions are associated with air quality cobenefits, they disagree about the impact on racial disparities—some finding substantial improvements and others finding little change (12–14). Furthermore, these previous studies are geographically limited to California and explore equity cobenefits as a by-product of climate policies rather than an explicit decision criterion.

Here, we first contextualize the current state and recent trends of national and state-level air quality disparities using existing best estimates of $PM_{2.5}$ concentrations across the contiguous United States. We then use a harmonized dataset of GHG and criteria air pollutant (CAP) emission sources as a baseline from which we can model the impact of changing GHG emissions on CAP emissions. We use this dataset to generate two types of illustrative NDC-constrained emission pathways, each of which represents a 50% reduction in total US GHG emissions with varying magnitudes and spatial distributions of coemitted criteria air pollution. We simulate outcomes of these pathways using an air quality model InMAP (15), which provides spatially explicit maps of $PM_{2.5}$ concentrations that result from specified emissions. We then aggregate these concentrations by race and ethnicity at state and national levels to assess impacts on

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both average exposures and exposure disparities. We also estimate costs for each pathway using a bottom-up approach for each sector independently that accounts for factors including up-front capital costs, regionally varying fuel costs, and estimates of operations and maintenance costs. More detail is available in the *Materials and Methods* and *SI Appendix*.

Our first set of pathways meet the US NDC by applying highly idealized decision criteria, targeting reductions based on income, race, or economic efficiency. In these pathways, we sort national emissions by the physical or socioeconomic characteristics of their source location and then remove GHG and copollutant sources from the top of the sorted list until the national GHG target is met. These represent extreme cases where national policy is carried out cohesively under one specific priority by removing all emissions from the most polluted regions (henceforth referred to as, *PM2.5 Exposure*), the neighborhoods with the highest fraction people of color (henceforth, POC), and the lowest income communities (henceforth, Income) and by removing the cheapest to abate carbon emissions (henceforth, Least cost). For example, in the Income pathway, we sort emissions by county-level median income and then remove all sources from the lowest income locations until the GHG target is met. The Equal pathway is the exception; we reduce GHG emissions proportionally by the same fraction from all point and nonpoint sources by an equal percentage such that the GHG target is met, reducing coemitted CAP emissions simultaneously. The second set of simulations meets the NDC by randomly reducing emissions from different sectors and regions to explore air quality impacts and trade-offs of a more idiosyncratic implementation of climate policy (*Materials and Methods*). As a reference, we also simulate the air quality using the unmodified 2017 National Emissions Inventory (NEI) (16) for all available emissions except those involving fires, which we refer to as Unmodified 2017.

Raw output concentrations do not match with observations for several reasons, including poorly constrained emission inventories; imperfect model parameterizations; simplified meteorology; and notably the omission of mostly nonanthropogenic emission sources such as forest fires, agricultural burning, sea salt, and desert dust (*SI Appendix*, Fig. S1). We therefore bias-correct our results using the best-available estimates of $PM_{2.5}$ (15, *Materials and Methods*) and present results as differences between simulations. Because anthropogenic and nonanthropogenic emissions are not fungible in their policy relevance, nonbias-corrected results are presented in *SI Appendix*. We present results both as exposures and as disparities; exposure is defined as the population-weighted mean $PM_{2.5}$ concentration, and disparity is subsequently defined as the percent difference between a given demographic's exposure and the population average exposure; both are calculated at national or state levels. A positive disparity means that a group is disproportionately impacted, and a decrease in disparity requires that a demographic has a larger reduction in exposure than the population average.

The combination of observations and simulations of $PM_{2.5}$ concentrations, aggregated into exposures and disparities, allows us to quantify past and potential future air quality and air quality equity impacts of changing emissions.

Results

For context, we first quantify historical air quality disparities in $PM_{2.5}$ exposures over the contiguous United States. Disparities are pervasive across racial and ethnic minority groups nationally and across the vast majority of US states (Fig. 1*A*) and although overall air quality in most of the United States improved over the past decade, disparities have generally increased. Intuitively, the

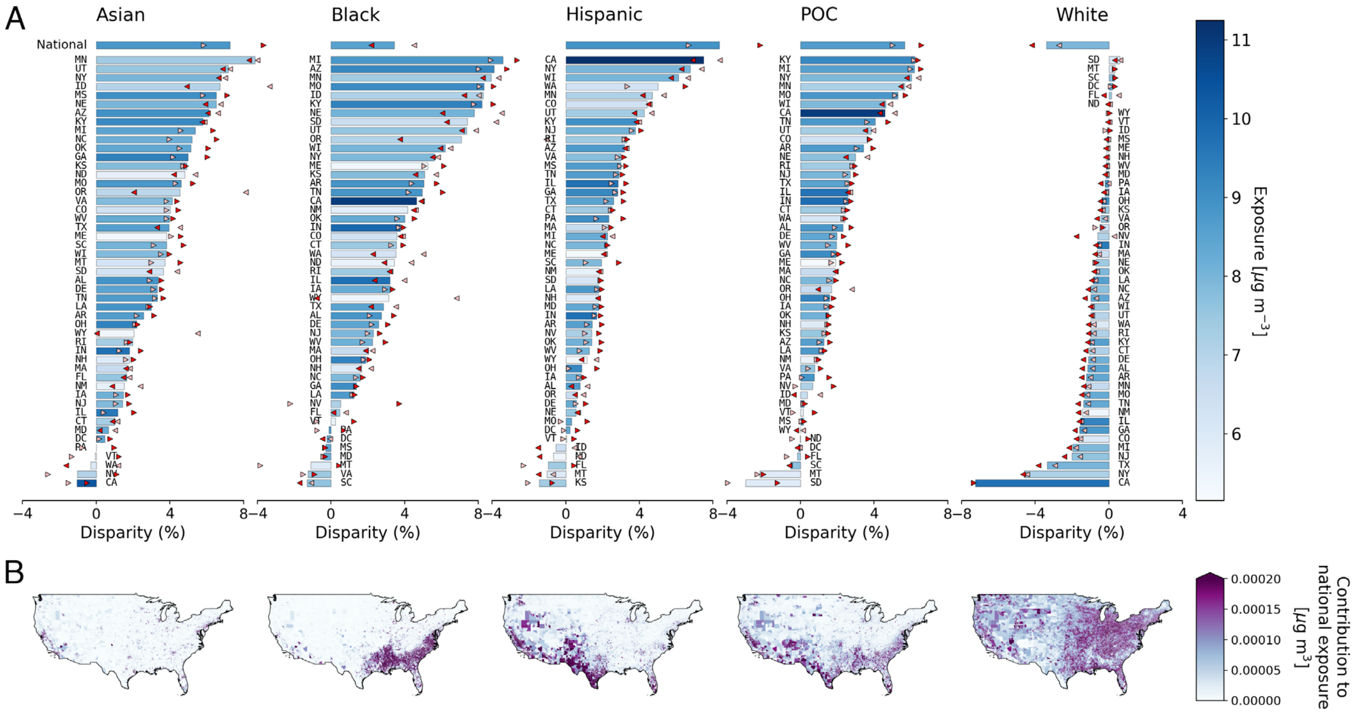

Fig. 1. National- and state-level relative disparities in air pollution exposure by race and ethnicity in the contiguous United States. (*A*) Bars indicate national (*Top*)- and state-level disparities for each racial/ethnic group. The bar color indicates the average absolute exposure to respirable particulate matter ($PM_{2.5}$) of each group within each state in the 2010s. The red triangles show 2010 (light red) and 2019 (dark red) disparities, estimated from fitting a linear trend through annual disparities. (*B*) Maps of the contribution of each tract to national disparities, which is calculated as the product of tract $PM_{2.5}$ concentration and the population of the specified group in each tract, divided by the total national population of that group. The sum of the national contributions values yields the population-weighted exposures for each group.

national average exposures for each demographic group are driven by the major population centers of those groups, which differ considerably for Asian, Black, and Hispanic communities (Fig. 1*B*). We find increases in disparities for POC nationally and in 37 of 48 states. Previous work has also found increasing disparities over time using different metrics and datasets (17). Sensitivity analyses like removing low-density census tracts yield consistent results (*SI Appendix*, Fig. S2). In this context of deepening environmental inequities, we look to understand the extent to which equity can be enhanced in parallel with GHG-mitigating climate policy.

To quantify how these disparities and exposures might change under climate policy, we model several idealized pathways to meet the national GHG emission reduction target. As described above, we target counties with high historical pollution, high fraction POC, low income, lowest cost of mitigation, and by equal fraction without any prioritization. We then simulate the air pollution distributions resulting from the new NDC-constrained emissions using InMAP. Output is aggregated to tracts, is bias-corrected, and used to calculate exposures and disparities of five racial/ethnic groups (*Materials and Methods*).

Every NDC-constrained pathway we constructed would reduce national $\mathrm{PM}_{2.5}$ exposure relative to the present day (*Unmodified* 2017), but reductions vary by 10 to 15% (between 0.8 and 1.2 $\mu\mathrm{g}\ \mathrm{m}^{-3}$, Fig. 2*A*). The estimated annualized costs for these pathways vary substantially, between about \$190 billion and \$340 billion, where the Least cost pathway is much less expensive than the rest (Fig. 2*C*; uncertainty analysis in *SI Appendix*, Fig. S3). Despite large methodological differences, the emission reductions in our Least cost pathway are largely consistent with the results from integrated assessment models, which simulate coupled energy systems (18). As shown in those models, we also find that reducing the majority of emissions from power plants and the transportation sector is required to meet targets and is more economical than decarbonizing other sectors (*SI Appendix*, Fig. S4).

In all pathways, White communities continue to experience lower-than-average exposures, while Asian and Hispanic communities continue to experience higher-than-average exposures (Fig. 2*B*), though absolute exposures decline in all cases (Fig. 2*D*). This highlights that the air quality cobenefits of implementing the US NDC are alone insufficient to overcome the long and pervasive history of disproportionate environmental impacts on minority communities (7, 19). National Black disparities consistently decline in all pathways, largely because anthropogenic emissions lead to more air pollution in the Eastern United States (*SI Appendix*, Fig. S1*A*), where Black people make up a larger portion of the population. Since these emissions must be reduced to meet the NDC, the pollution in the Eastern United States declines disproportionately. This finding is consistent with recent historical trends (Fig. 1). We note, however, that the magnitude of the national Black disparities depends strongly on the bias correction, which incorporates missing nonanthropogenic emission sources as well as model biases. When considering only uncorrected anthropogenic emission from the Environmental Protection Agency (EPA) inventory, Black communities are the most disproportionately impacted group by a substantial margin and the pathways have little impact on the total disparities (*SI Appendix*, Fig. S5), highlighting the potentially consequential influence that inclusion of nonanthropogenic sources in air quality baselines could have on setting national-scale air quality equity priorities.

Substantial variation in disparities (Fig. 2 *A* and *B*) and exposures (Fig. 2 *C* and *D*) exists between pathways, ranging from

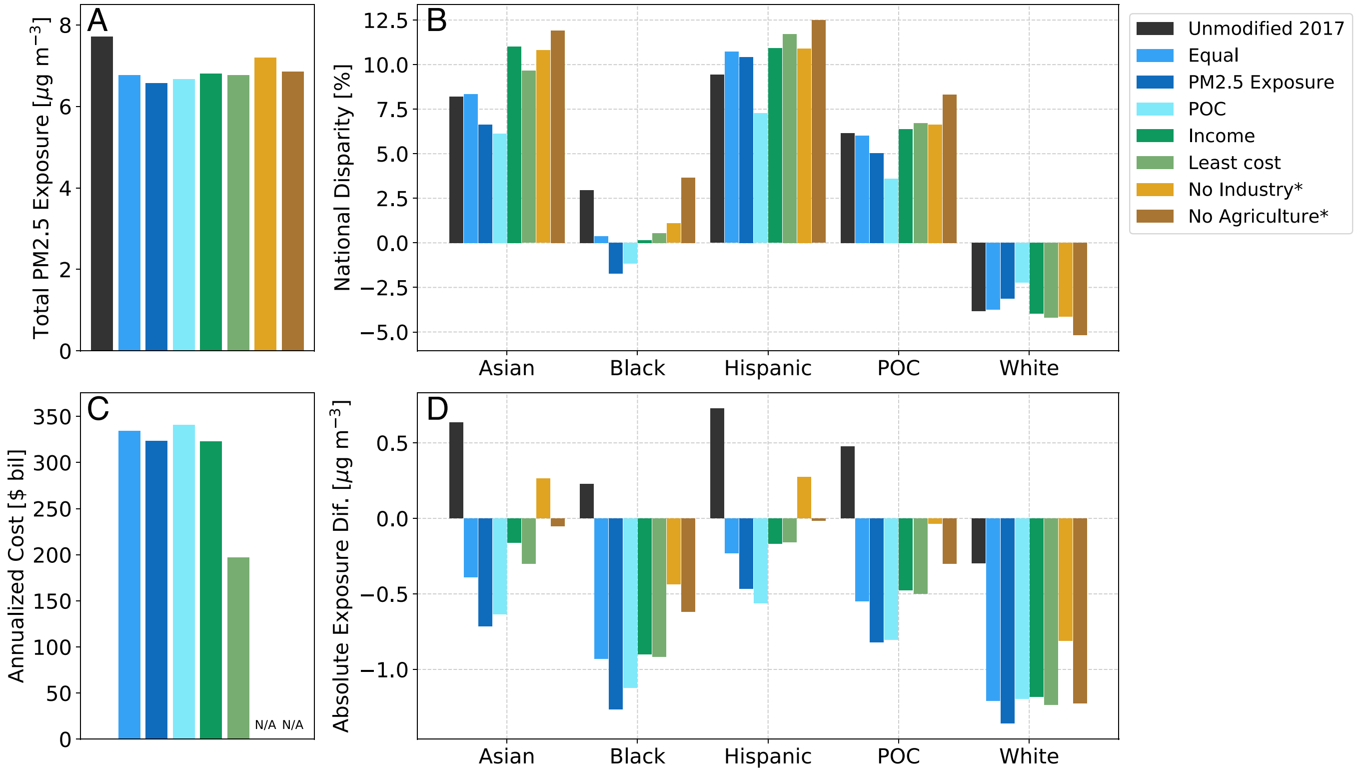

Fig. 2. Exposures and disparities of $\mathrm{PM}_{2.5}$ after implementing idealized policy priorities to meet emission reduction targets. (*A*) Total average national PM exposure, (*B*) national disparities by demographic group, (*C*) annualized costs of mitigation, and (*D*) absolute exposure difference by demographic group. Absolute exposure difference refers to the difference in exposure from the Unmodified 2017 total exposure in (*A*). All pathways lead to reductions in absolute $\mathrm{PM}_{2.5}$ exposures and entail annualized costs of \$190 to 340 billion. The No Industry and No Agriculture simulations, marked with asterisks, are not NDC constrained and do not have cost estimates.

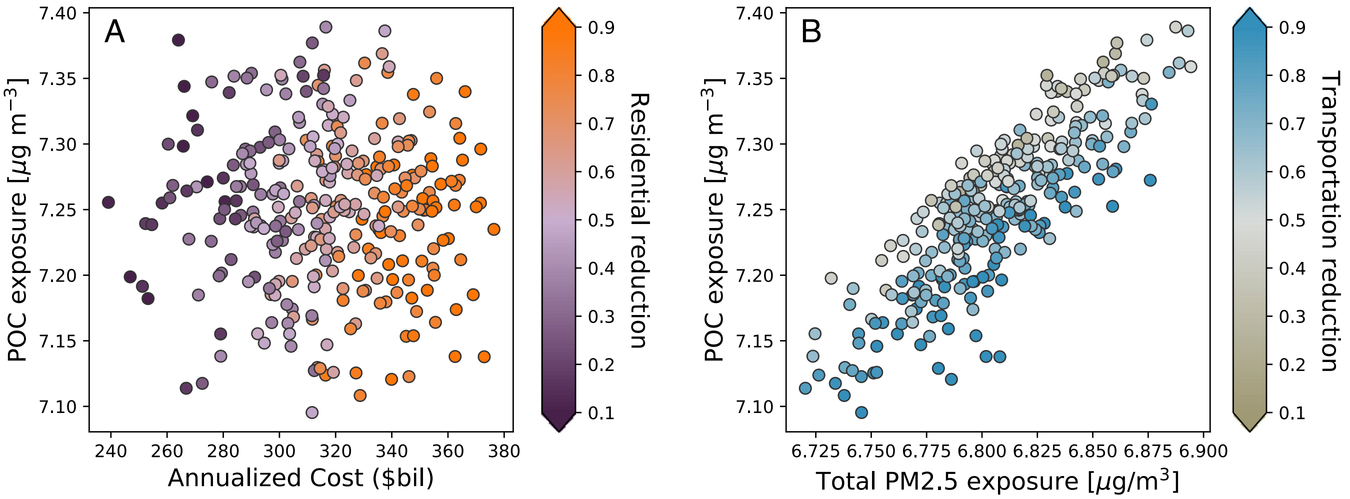

Fig. 3. Sectoral influence in randomized experiments. National POC exposure as a function of cost, colored by reductions in residential emissions (*A*), and national population–average exposure colored by reductions in transportation emissions (*B*). There is little relationship between cost and POC exposure, but POC exposure and total exposure are strongly correlated. Costs in the randomized experiments are strongly dependent on the residential sector (*A*) and POC exposures tend to be lower when more transportation emissions are reduced (*B*).

−2 to 0% for Black communities and 8 to 12% for Hispanic communities (Fig. 2*B*). A national prioritization of emission reductions in communities of color (POC pathway) is the only pathway explored here that reduces disparities for all non-White groups. While in some cases climate policy can be used as a means to reduce inequity in air pollution exposure in the United States, there is no guarantee that cutting GHG emissions will lead to that result. Indeed, relative to the baseline represented by Unmodified 2017, inequities can be amplified under certain climate policy priorities, including two pathways that represent economically and politically favorable priorities: the Least cost pathway, and the Income pathway, which prioritizes low-income communities—a common proxy for racial and ethnic dimensions of environmental injustice, including in contemporary climate-related regulations (2).

For all demographics, the exposure reduction from implementing any iteration of the NDC is larger than the variation between the different idealized pathways (Fig. 2*A*), emphasizing the robust air quality cobenefits of GHG emission reductions. State exposures and disparities are affected similarly to the national exposures and disparities (*SI Appendix*, Fig. S6); exposures decline, while disparities remain roughly constant.

For comparison, we also conducted No Industry and No Agriculture simulations, which are not constrained by the NDC, and therefore have quite different GHG emission reductions than those of the NDC-constrained pathways. These sectors are not comprehensively represented in our pathways due to both current technological limitations for decarbonization and practical data limitations, so to illustrate that their omission does not drive our finding of residual disparities, we demonstrate their individual impacts by modeling $PM_{2.5}$ distributions without their criteria pollutant emissions. Completely removing the emissions from these sectors does not diminish disparities, though it would convey large total air quality benefits.

We next implemented a set of 300 randomized climate policy experiments, still constrained by the NDC, but no longer based on idealized decision criteria. Instead, GHG emissions and their accompanying coemissions are randomly removed throughout the country until the NDC target is met (*Materials and Methods*). The randomly removed emissions are by design less targeted than the idealized pathways and therefore the variation in total and demographic-specific exposures between the randomized experiments is roughly half as large as from the idealized decision pathways (*SI Appendix*, Fig. S7). However, this spread still allows us to explore relationships (or lack thereof) between the properties of different pathways and their outcomes.

For example, there is little correlation between national POC pollution exposure and national policy cost (Fig. 3*A*), implying that it may be possible to implement national GHG emission reduction while optimizing air quality equity, without substantially increasing costs. However, as shown using the minimum cost pathways above, simply ignoring the equity dimension and focusing entirely on cost can still worsen air quality disparities, so implementation would need to be sectorally and spatially targeted. We also show that residential electrification is largely responsible for higher pathway costs (Fig. 3*A*), though industry also contributes to a lesser extent (*SI Appendix*, Fig. S8*D*). The strong correlation between total population exposure and national POC exposure (Fig. 3*B*) indicates that these two outcomes are tightly coupled across pathways. However, residual variation in POC exposure is strongly associated with the magnitude of emission reductions from the transportation sector. The reverse pattern is true for the electricity sector (*SI Appendix*, Fig. S8*G*), in part because electricity and transportation are the largest sources of GHG emissions, so NDC-constrained random pathways with high transportation emission reduction are also associated with low electricity emission reduction.

Transportation emissions drive differences in disparities between randomized pathways, as illustrated in Fig. 4, which summarizes the national and state disparity changes and shows the impact of removing transportation emissions on exposures and disparities (Fig. 4 *C* and *F*). Since each randomization includes a different combination of sectoral reductions, we are able to demonstrate that transportation reductions reduce disparities and exposures disproportionately for POC (changes from all sectors are shown in *SI Appendix*, Fig. S9). Each randomization is associated with a new set of national disparities (Fig. 4*A*). Black disparities decrease relative to present day, while Hispanic and Asian disparities increase, and POC and White disparities remain relatively similar, though the slight skew toward increases and decreases, respectively. The difference between the distributions is substantially smaller without bias correction (*SI Appendix*, Fig. S10), but the relative

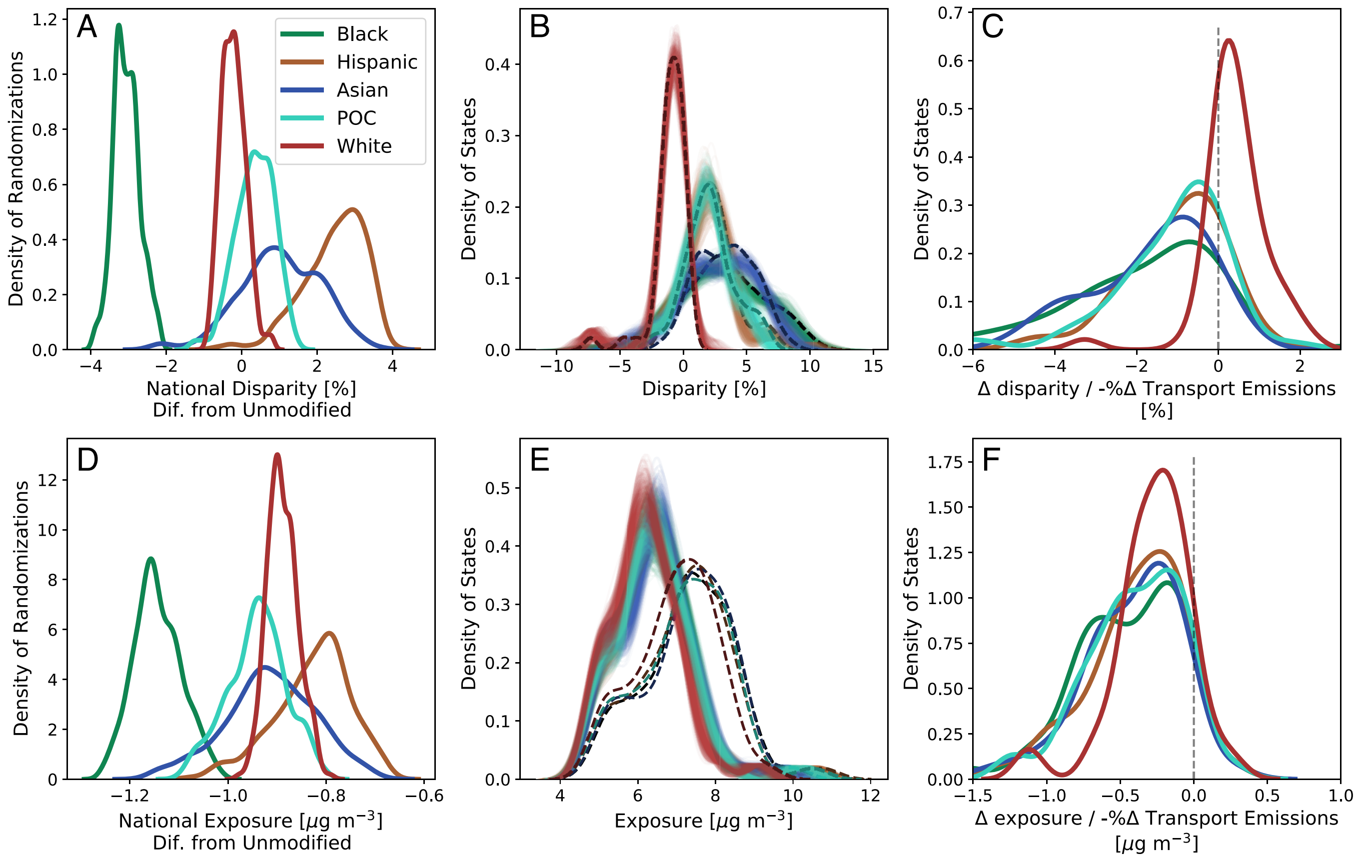

Fig. 4. Disparity and exposure changes and transportation influence in randomized experiments. (*A*) Distributions of changes in national disparity relative to the Unmodified 2017 case for each randomized experiment (N = 300 per distribution) (*B*) Distribution of state disparities (N = 48 per distribution) in each randomized experiment (faint solid lines, N = 300 distributions) and the Unmodified 2017 case (darker dashed lines). (*D* and *E*) Equivalent distributions as for (A) and (*B*), using exposure instead of disparity. (*C* and *F*) Distributions of state-level linear regression coefficients (N = 48 per distribution) from modeling disparity (*C*) and exposure (*F*) using fractional change in all the four sectors; only transportation coefficients are shown as they have the most disparate impact.

positions are similar. The increase in Hispanic and decrease in Black disparities are consistent with recent historical trends (Fig. 1), as are the skews for POC and White disparities. All exposures decline as a result of emission reduction (Fig. 4 *D* and *E*), which reiterates the cobenefits of climate policies. Distributions of state disparities remain largely unchanged (Fig. 4*B*), but reductions in transportation emissions are associated with disproportionate exposure and disparity reductions (Fig. 4 *C* and *F* and *Materials and Methods*). In most states, transportation emission reductions improve air quality for all demographics while simultaneously exhibiting large equity cobenefits compared to other sectors. Residential emissions demonstrate a similar but less pronounced pattern (*SI Appendix*, Fig. S9).

Discussion

Our results suggest that it is indeed possible to reduce, but not eliminate, air pollution exposure disparities through targeted implementation of climate policy. We find that the largest disparity reductions arise from directly targeting emission reductions in communities of color, but explicit consideration of race in environmental policy has thus far been explicitly avoided to limit potential legal challenges (20). We find that strategies that avoid this political and legal sensitivity by targeting income, cost, or equal fractions across sectors and counties are not particularly effective at reducing disparities. The use of historical pollution exposure (PM2.5 Exposure pathway) for targeting is moderately effective at reducing disparities (Fig. 2*B*), and even more effective at reducing relative exposures (Fig. 2*D*). This implies that explicitly targeting air pollution reduction in communities with historically high pollution, as is done in some contemporary US climate policy, could reduce racial pollution disparities, though the continued use of income could have the opposite effect.

As with all modeling studies, our results are subject to model bias and model limitations. InMAP, the reduced complexity air quality model used here, only outputs annual average outdoor $PM_{2.5}$ and therefore does not capture daily or seasonal variations; indoor air quality; or the impact of air pollutants such as NOx, ozone, or heavy metals. The inputs are based on one national emission inventory and 1 y of meteorological dataset, which are imperfect and do not capture the interannual variability of meteorology or human behavior. However, the high spatial resolution and low computational time allow us to run many simulations and calculate racial/ethnic pollution exposures and disparities.

Disparities and exposures are both useful metrics for air quality equity. Disparities are a socially and ethically relevant concept, and a stated priority of the US federal government, while exposure translates directly to health impacts and observations. If changes in disparity and changes in exposures are not perfectly correlated, some amount of exposure reduction may be substituted for additional disparity reductions. Although such a pathway is possible, this trade-off appears unlikely to occur in practice when policies are constrained by a GHG emission target (Fig. 3*B*). As has been previously proposed, prohibiting unequal exposure changes from new projects that require environmental impact assessments (e.g., freeways and power plants) would decrease differences over time (21), which would inevitably also lead to decreases in disparities.

We only address the impact of emissions that are not directly anthropogenic, like desert dust and wildfire smoke, through a bias correction. These emissions are not an input to the model and therefore are also not included in our NDC implementations. However, despite confounding factors such as inherent model bias, we interpret the bias correction as an approximate incorporation of these missing emissions (*SI Appendix*, Fig. S1*C*). Generally, the inclusion of these sources results in a decrease in disparities for POC. In particular, given that a larger fraction of the Black population lives in the eastern half of the United States, the national-scale Black disparity is decreased because the correction decreases the contrast between the eastern and western halves of the country (*SI Appendix*, Fig. S1). Wildfires, in particular, have more annual variation in their intensity and location compared to regulated emission sources and have been increasing in magnitude in recent years (22). This trend has renewed efforts to better understand the health impacts of short-term vs. long-term exposure to smoke (23) and of wildfire smoke vs. other PM (24), as well as the equity of access to indoor air pollution control (25). Whether wildfires and similar types of sources should be included directly when calculating disparities depends on the policy objective. Health impacts are largely a function of exposure, so if the primary focus of a policy is inequity in health outcomes, then "natural" sources like wildfires are clearly pertinent. However, if the primary focus of a policy is addressing the structural inequities around, for example, siting of emission sources, wildfires are less relevant.

All emission reductions considered here as part of our NDC implementations are associated with improved air quality. Emission sources are rarely evenly distributed across populations, which makes crafting policy to address disparities more complicated. Industrial emissions have long been a focus of environmental justice concerns because industrial facilities have often been intentionally colocated with communities of color (26, 27). However, our No Industry simulation and randomized experiments suggest that even large-scale industrial facility removals may not substantially reduce disparities. It is worth noting, however, that we do not analyze the impact of individual facilities, some of which are likely to have large equity cobenefits from reduced or removed emissions.

Among all the anthropogenic sectors considered here, we identify transportation as having the greatest potential for reducing pollution in communities of color via climate policy (Fig. 4*C* and *SI Appendix*, Fig. S9). Recent empirical studies also found that transportation impacts are inequitable, though not in the context of GHG reduction (28). We have assumed that electrified transportation will not require new fossil fuel–based electricity generation, which is not guaranteed. This result for transportation should therefore be interpreted as a first-order estimate of removing on-road emission sources as part of climate policy, not an exhaustive representation of a full energy system that couples transportation, electric power generation, and other sectors as is often done in transportation-specific studies (29). Studies that do include this coupling have shown that population-average health benefits are concentrated in the Western United States, but present everywhere in the United States when grid electricity is largely from renewable sources (30).

One challenge when creating policy to address air quality equity is that such policies target pollution sources, not pollution receptors. We have assumed in the design of our simulations that proximity to impacted communities is a good proxy for reducing concentrations in those communities; in other words that the sources causing inequitable pollution are located in the communities experiencing the inequities. Although this may often be true, the transport and transformation of pollutants through variable meteorological and chemical background conditions can complicate this relationship. In the case of transportation, the relationship between the source and the receiver of pollutants is further complicated by the sources' mobility. Infrastructural and economic inequities mean that the people or organizations responsible for the pollution are often not those who experience the burden (21, 31). Therefore, policies that promote pollution reduction may incentivize infrastructural improvements outside of the impacted communities. Although such policies may help address air quality inequities, they may have consequences in other equity dimensions like procedural justice and the economic inequality from investments, that are beyond the scope of this study, but are nonetheless important considerations in equity-focused policy design.

With these considerations in mind, a variety of policy options exist for addressing transportation emissions. Low maintenance and fuel costs have made electric vehicles (EVs) more cost competitive, but they are still currently more expensive than their fossil fuel counterparts. Government programs that decrease the price difference between the two options would incentivize a faster transition. This could include rebates or tax breaks for EVs, increased gas tax, subsidized at-home or public charging infrastructure, or differentiation in vehicle registration costs. Financially or infrastructurally incentivizing alternative modes of individual transportation (e.g., walking, bicycling) or modes powered by renewable energy (e.g., electric rail, electric bus, e-bikes) (32) could achieve the same air quality benefits as replacing the current fleet of fossil fuel vehicles with their electric counterparts. Furthermore, these alternatives are less energy intensive than cars and trucks, and therefore require smaller increases in renewable capacity to power them with renewable energy.

Increased air quality equity is not an inevitable consequence of climate policy. However, progress toward the NDC's equity objectives is possible with explicit consideration of the distribution of pollution reduction cobenefits. Emission reductions in the transportation sector have the greatest potential to address pervasive air pollution inequities. So, although climate policy alone is unlikely to eliminate all air quality disparities, investing in clean transportation and prohibiting disparate exposure changes from new capital projects can help meet the NDC goals of mitigating climate change while also improving environmental justice at both state and federal levels.

Materials and Methods

Historical $PM_{2.5}$ Exposure. We use annual Washington University in St. Louis (WUSTL) surface $PM_{2.5}$ concentrations, V5.GL.02. (16), which combine satellite data, surface measurements, and modeling results to form a best estimate of historical $PM_{2.5}$ distributions and were shown to have an annual R^2 over North America of 0.57 or 0.67 when compared to only World Health Organization-collocated sensors. For trends in Fig. 1, we use the mean of annual data within 2 years of 2017, meaning 2015 to 2019. We aggregate the 0.01 × 0.01 degree resolution dataset to census tracts using area weighting. Tracts have been shown to be a sufficiently high resolution for estimating disparities (33). We use ACS5 (2013 to 2017) population estimates for exposure and disparity calculations.

Emissions. We use the most recent (2017) NEI from the EPA as the underlying emission dataset. As this study is focused on potential cobenefits of climate policy, we require inventories of both criteria pollutants and GHGs. The NEI includes some, but not all GHG emissions. Most notably for this analysis, residential and oil & gas (O&G) GHG emissions are missing. Therefore, we estimate residential GHGs using EPA emission factors and estimate O&G GHGs by running the same emissions calculations as used in the NEI for the criteria pollutants (see *SI Appendix* for more detail). Some emission sources were aggregated and others disaggregated using proxies (*SI Appendix*). GHG and CO_2e are used interchangeably, where CO_2e is the sum of CO_2, CH_4, and N_2O, weighted by their respective GWP100 (CO_2: 1, CH_4: 25, N_2O: 298). The emissions and their respective sector categorizations have been made available through the Harvard Dataverse.

Idealized Decision Pathways. The five idealized pathways (Equal, PM2.5 Exposure, POC, Income, and Least cost) were designed to heuristically explore the implications of a wide range of decision criteria. Total GHG emission cuts in each of these pathways meet the 50% reduction target and at least 80% reduction of GHG emissions of electricity generation, in approximate accordance with the 2035 100% clean electricity target. The Equal pathway does not have this 80% criterion, because emissions are removed equally from all sources to meet the NDC. The other pathways use one county-level criterion to rank all accounted emissions from the continental United States and remove sources sequentially until the NDC has been met (more detail in *SI Appendix*). The county ranking for the PM2.5 Exposure pathway is based on 2015 to 2019 average $PM_{2.5}$ concentrations from the WUSTL dataset to limit the impact of interannual variability when determining the most polluted regions. The rankings for the POC and Income pathways are based on the county-level version of the 5-y (2013 to 2017) American Community Survey (ACS5) from the US Census Bureau. For the POC pathway, we use the non-White, non-Hispanic fraction of the population and for the income pathway, we use the median income.

Both the GHGs and the criteria pollutants of the selected sources are set to zero, thereby directly coupling the GHG emission sources. Not every emission source was considered for removal–we limit the analysis to power plants, on-road transportation, residential fossil fuel use, and a subset of industrial emissions: cement plants, steel plants, pulp and paper plants, petroleum refineries, and oil & gas production; not all criteria pollutants are removed from these sources because we assume carbon capture and storage (*SI Appendix*).

Randomized Experiments. No idealized decision criteria is imposed for the randomized experiments. Instead, we randomly select a national fractional reduction of electricity, transportation, residential, and industrial emissions required to meet the NDC. This was done by initializing a fraction from a random uniform distribution for each sector. We then calculate the total resulting emission reduction from the initialization and randomly select a sector to increment slightly; we repeat this process until we have a set of fractions that meet the GHG reduction criteria. After selecting a fraction for each sector, sources are randomly eliminated from around the country until those fractional reductions are fulfilled, again completely removing all GHGs and criteria pollutants from each source. Due to their mobile nature, we also remove nearby county emissions when removing transportation emissions (*SI Appendix*).

Coefficients describing the change in exposure or change in disparity as a function of fractional reductions in each sector (Fig. 4) are conducted using ordinary least squares:

$$disparity_{run}^{group} = c_{ele} \cdot f_{run}^{ele} + c_{tra} \cdot f_{run}^{tra} + c_{ind} \cdot f_{run}^{ind} + c_{res} \cdot f_{run}^{res} + c_0 + \varepsilon_{run},$$

where f is the fractional reduction in each sector's GHG emissions (shown as superscript) and each simulation (run) is a point in the regression. This is repeated for each state. The resulting coefficients (e.g., c_{tra} for Fig. 4*C*) are plotted as distributions.

Air Quality Modeling. To simulate air quality, we ran InMAP version 1.8 over the continental United States with the default variable grid configuration (15). InMAP is a reduced complexity model (RCM) that finds an annual equilibrium solution using user-defined input emissions. The variable grid means that locations with higher population density have smaller horizontal resolution, which is helpful for quantifying air pollution disparities. The model output resolution is variable, with very low resolution of around 50 km in low population density areas and very high resolution of up to 120 m in populated areas. To make results comparable, both to observations and between simulations, we aggregate the output to census tracts using area weighting.

Area emissions were allocated to appropriate subcounty regions using spatial surrogates. On-road emissions were allocated to roads using annual average daily traffic from the Department of Transportation. Heavy trucks are limited to Interstates, Freeways, and Expressways. Residential emissions were downscaled to tracts using 2017 ACS5 tract population. Ship, port, rail, and agricultural emissions were also allocated using proxies (*SI Appendix*) though they are not modified in our pathways. Shapefiles of the input emissions for the idealized pathways have been made available through the Harvard Dataverse.

InMAP is a useful tool for this type of study because it is computationally inexpensive and can therefore be used to run many more simulations than would be possible with a more conventional chemical transport model. However, despite the high spatial resolution, the temporal resolution is limited to annual, and the model only uses one one set of meteorological data. Furthermore, there is no modeling of NOx, ozone, or other air pollutants, and as with any atmospheric model results depend on parameterizations and the quality of input data. These limitations are relevant to the interpretation of this and other studies based on RCMs.

Bias Correction. We applied a tract-level bias correction using 2015 to 2019 mean surface $PM_{2.5}$ data from the WUSTL dataset described above. We regrid both the InMAP simulation output and the gridded WUSTL dataset to the tract level using area weighting. We take the difference between the InMAP simulation that uses the unmodified inventory, and the WUSTL dataset, and use that difference as the correction for all InMAP output such that $PM_{2.5}$ absolute differences between the simulations remain unchanged but baseline concentrations are better represented (*SI Appendix*, Fig. S1). We believe this better represents the true distribution of $PM_{2.5}$ and allows the model to define the differences. Many of our figures are repeated in *SI Appendix* without this bias correction to demonstrate that this methodology does not fundamentally impact the interpretation of our results.

Costs. We estimate costs of the NDC-constrained pathways using different bottom-up approaches for each sector. All costs are estimated relative to a fossil fuel–dependent alternative. These estimates are not intended to be exact, but rather to illustrate differences between pathways in a self-consistent manner. They represent total societal costs and do not differentiate by the different actors that may bear the burden of the costs. The costs are spatially and sectorally heterogeneous, but otherwise linear (e.g., electrifying half of cars in a certain county costs half as much as electrifying all of them). All costs, after adjusting for inflation to 2020 US dollars, reflect the changes required to meet the 2030 mitigation targets and are annualized using a 5% interest rate assuming that the costs continue over time (unless otherwise specified).

Electricity sector costs are estimated as the cost of replacing existing fossil fuel power plants with the cheapest available renewable energy generation in the region using the input files to the USA Global Change Analysis Model (GCAM-USA). These costs include capital cost, grid interconnection cost, operating and maintenance cost, and fuel cost. Transportation costs are estimated as the cost of electrifying the fleet, using capital and maintenance costs based on GCAM input files and using vehicle miles traveled from the Federal Highway Administration and GCAM energy intensities for fuel costs. Residential costs are calculated as the premium required to decarbonize residential sources, specifically to electrify space heating, water heating, stoves, and dryers that are powered by natural gas, propane, or fuel oil/kerosene. This relies on purchasing costs from the gray literature and the Residential Energy Consumption Survey for fuel costs. As described above, only some industrial sources are removed in the pathways. Since refineries and O&G facilities can be completely removed in our simulations, costs are based on the value-added estimates from the US Bureau of Economic Analysis, excluding the gross operating surplus since this is not a component of societal value. For cement, steel, and pulp and paper facilities, we use the cost of implementing carbon capture and storage from Leeson et al. (34). Details of all cost calculations are available in *SI Appendix*.

Data, Materials, and Software Availability. Previously published data were used for this work [ref. 16, EPA National Emissions Inventory (2017) https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data].

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